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GOLD AVAILABILITY—WORLD

A Minerals Availability Appraisal

By Paul R. Thomas and Edward H. Boyle, Jr.

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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PREFACE

The Bureau of Mines is assessing the worldwide availability of selected minerals of economic significance, most of which are also critical minerals. The Bureau identifies, collects, compiles, and evaluates information on producing, developing, and explored deposits, and mineral processing plants worldwide. Objectives are to classify both domestic and foreign resources, to identify by cost evaluation those demonstrated resources that are reserves, and to prepare analyses of mineral availability.

This report is one of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources. Questions about the Minerals Availability Program should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E Street NW., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

d/yr	day per year	mt	metric ton[2]
°F	degree Fahrenheit	mt/d	metric ton per day
ft	foot	mt/yr	metric ton per year
g	gram	pct	percent
g/mt	gram per metric ton[1]	ppm	part per million
ha	hectare	st	short ton
kg	kilogram	tr oz	troy ounce[3]
km	kilometer	tr oz/yr	troy ounce per year
m	meter	wt pct	weight percent
m^3	cubic meter	yr	year

GOLD AVAILABILITY—WORLD

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By Paul R. Thomas[1] and Edward H. Boyle, Jr.[2]

ABSTRACT

The Bureau of Mines evaluated the long-term cost and availability of primary gold production from 135 mines and deposits worldwide. Collectively, the evaluated countries represent 93 pct of world gold production. Total recoverable gold available (as of January 1984) from a subset of 111 significant producing mines and developing deposits in 13 market economy countries (MEC's) is estimated at 810 million tr oz. The Republic of South Africa is estimated to account for 87 pct of total recoverable gold. The United States and Canada account for 4 and 4.5 pct of the total, respectively. Eighty-three percent of total recoverable gold is available at a constant 1984 break-even price of $400/tr oz, and 70 pct is available at $300/tr oz. South Africa accounts for 90 pct of the gold available at $400/tr oz or less.

Major conclusions are that (1) South Africa should remain the largest world producer through the year 2000, (2) annual MEC output in 2000 should not be significantly different than current output given constant 1984 gold prices of more than $300/tr oz, and (3) there may be a significant decline in production after 2010 in the absence of major new discoveries and continued development of new mines to offset the depletion of the South African mines.

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INTRODUCTION

Since the late 1970's the world gold mining industry has been characterized by dynamic growth in production and volatility in price. World production in 1983 was almost 15 pct greater than in 1980, and the short-term trend continues upward. Annual dollar-based price changes since the early 1970's have been unprecedented in both magnitude and volatility. This commodity, which sold for $35/tr oz[3] for over a third of a century, reached an annual average $612/tr oz in 1980. Until 1980, the future price of gold seemed set on an upward trend. Since that year, however, world gold prices have fallen by over 50 pct to slightly over $300/tr oz at the end of 1984.

Against this background, this study was undertaken to determine (1) the level of world demonstrated gold resources, (2) total and annual availability of gold mine production, (3) long-run production costs per operation and by national aggregates, (4) the economic and technical factors that impact upon cost and availability, and (5) probable future mine production and cost trends.

One statement concerning the results of this study must be made at this point: the unprecedented rise in the price of gold, especially beginning in the mid-1970's, caused exploration and new mine development to expand worldwide at a rapid pace. This pace has continued through 1984, even given the decline in U.S. dollar gold prices since 1980. One reason is the poor economic outlook for base metals, which by comparison renders gold an attractive investment alternative for the mining industry in general. During the last few years, gold exploration results, mine expansions, and new mine developments have been reported on an almost daily basis. This increase in activity has been most evident in major producing nations such as the United States, Canada, Australia, and Brazil, although seemingly every nation is experiencing some activity. Even South Africa, the industry leader which as recently as 1981 was being written off as a rapidly dwindling producer, has increased its level of production, resources, and new mine development since 1980. The outlook for future gold price and production response, however, remains one of uncertainty.

Table 1 lists the evaluated primary gold operations by nation and productive status. This list consists of 135 primary gold mines and deposits which were subjected to complete evaluation to determine demonstrated resources and long-run total production costs. These 135 properties represent the great majority of known gold resources and annual production in the market economy countries (MEC's). The study also presents recent information on approximately 65 other (mostly small) properties in various stages of development or initial production. These other properties are all new developments that have been reported in the literature within the last 3 yr. They are perhaps the best indicator of the intense level of dynamic activity that has characterized the world gold industry in recent years. In addition to the above primary mines and deposits, over 200 base metal mines and deposits were evaluated to determine byproduct gold content.

No other commodity throughout history has maintained the economic and political importance of gold, and with the possible exception of oil, no other commodity has undergone so much rigorous analysis by so many individuals, companies and nations. This Bureau of Mines appraisal makes a unique contribution to this body of literature as a result of its extensive mine coverage and the detailed engineering and economic cost analyses that it has produced.

ACKNOWLEDGMENTS

Domestic and foreign data collection were performed under contract by Morrison-Knudsen Co., Inc., Boise, ID, and Davy-McKee Corp., San Ramon, CA. Personnel of the Bureau's Minerals Availability Field Office, Denver, CO, evaluated the data and performed the engineering and economic evaluation analyses.

COMMODITY OVERVIEW

Gold is a unique mineral commodity in that it is, above all, an alternate store of wealth to fiat currencies, most notably the U.S. dollar. The U.S. dollar serves as the primary medium of exchange in international transactions and is the currency in which world gold prices are denominated. For that reason, the following interactive factors all impact directly upon the demand for, and price of, gold:

1. The level of U.S. interest rates;
2. General inflationary trends and expectations;
3. The rate of growth in U.S. money supply;
4. The exchange rates between the U.S. dollar and other major currencies;
5. The balance of payments position in U.S. trade accounts;
6. Government budget deficits;
7. Perceived or real economic, political, or natural crises, etc.

The great majority of gold is held either as an investment medium or as a form of insurance to hedge against uncertainty about the value of fiat currency or potential disaster. Only a small percentage of the world's total gold production has been consumed in industrial applications, and much of that metal will eventually be recycled.

Gold is a unique mineral commodity also in that long-term production cost increases do not in and of themselves imply rising market prices as is the general case with base metals. This is because typical world annual production of

[3]The troy ounce = 31.1035 g.

Table 1.—Primary gold mining operations included in the availability study

Country and operation name	Type[1]	Status as of January 1984[2]
Australia:		
Central Norseman	U	P
Fimiston Leases	U	P
Hill 50-Morning Star	U	P
Mt. Charlotte	U	P
Mt. Morgan Tailings Project	SD	P
North Kalgoorlie	U	P
Telfer	S	P
Bolivia: Teoponti	SD	P
Brazil:		
Morro Velho	U	P
Serra Pelada	S	P
Canada:		
Agnico-Eagle (Gold Div.)	U	P
Camflo-Malarctic Hygrade	U	P
Campbell Red Lake	U	P
Con-Rycon	U	P
Detour Lake	U	P
Dickenson	U	P
Dome	U	P
Giant Yellowknife	U	P
Golden Giant (Hemlo)	U	N
Kerr Addison	U	P
Lac Minerals (Hemlo)	U	N
Ladner Creek	U	P
Lupin Project	U	P
Macassa (Willroy)	U	P
Pamour Porcupine	U	P
Sigma	U	P
Specogna	S	N
Teck-Corona (Hemlo)	U	N
Chile: El Indio	U	P
Colombia:		
El Bagre	SD	P
La Salada	U	P
Dominican Republic: Pueblo Viejo	S	P
Ghana:		
Ashanti	U	P
Prestea	U	P
Tarkwa	U	P
Mexico: Pinzan Morado	U	N
Philippines:		
Benguet Gold Operations	U	P
Masbate	S	P
Paracale	U	P
Republic of South Africa:		
Beatrix	U	P
Blyvooruitzicht	U	P
Bracken	U	P
Buffelsfontein	U	P
Consolidated Modderfontein	U	P
Deelkraal	U	P
Doornfontein	U	P
Dreinfontein Consolidated	U	P
Durban Roodepoort Deep	U	P
East Rand Proprietary Mine	U	P
Egoli Consolidated (East)	S	P
Egoli Consolidated (West)	S	P
Elandsrand	U	P
Ergo (East Rand Au & U Co.)	S	P
E. T. Consolidated	U	P
Fairview (Barberton Mine)	U	P
Free State Geduld	U	P
Grootvlei	U	P
Harmony	U	P
Hartebeestfontein	U	P
Joint Metallurgical Scheme	S	P
Kinross	U	P
Kloof	U	P
Leslie	U	P
Libanon	U	P
Loraine (Allanridge)	U	P
Marievale	U	P
President Brand	U	P
President Steyn-Video	U	P
Randfontein Estates	U	P
RMMM Slimes Project	S	P
Simmer and Jack	U	P
St. Helena	U	P
Stilfontein	U	P
Unisel	U	P
Vaal Reefs	U	P
Venterspost	U	P
Village Main Reef	S	P
West Rand Consolidated	U	P
Western Areas	U	P
Western Deep Levels	U	P

Table 1.—Primary gold mining operations included in the availability study—Continued

Country and operation name	Type[1]	Status as of January 1984[2]
Western Holdings Complex	U	P
Winkelhaak	U	P
Witwatersrand Nigel	U	P
Taiwain: Chinkuashih	U	P
United States:		
Alaska:		
Apollo	U	N
Bear Creek	S	P
Big Hurrah	S	P
Chicken Unit	S	P
Circle Unit	S	P
Fairbanks Unit	S	P
Golden Zone	U	N
Independence	U	N
Kougarok District	S	P
Livengood Placers	S	P
Mikado	U	P
Nome Beaches	S	P
Peters Creek	S	P
Solomon Unit	S	P
Tuluksak Dredges	S	P
Wiseman Unit	S	P
California:		
McLaughlin	S	N
Royal-Mountain King	S	N
San Juan Ridge	S	N
Yuba Placer Operations	SD	P
Colorado: Victor Project	S	P
Idaho:		
Homestake-Yellow Pine	S	N
West End-Garnet Creek	S	P
Michigan: Ropes	U	N
Montana:		
Golden Sunlight	S	P
Zortman-Landusky	S	P
Nevada:		
Alligator Ridge	S	P
Battle Mountain	S	P
Borealis	S	P
Carlin Operations	S	P
Goldfield Project	S	N
Jerritt Canyon	S	P
Pinson-Preble-Ogee	S	P
Round Mountain	S	P
Windfall	S	P
New Mexico: Ortiz	S	P
South Dakota: Homestake	U	P
Utah: Mercur	S	P
Washington: Knob Hill	U	N
Zimbabwe:		
Arcturus	U	P
Athens	U	P
Blanket	U	P
Dalny	U	P
How	U	P
Mazoe	U	P
Muriel	U	P
Old West-Redwing	U	P
Patchway-Brompton	U	P
Renco	U	P
Shamva	U	P
Venice	U	P

[1]S—surface, SD—surface (dredging), U—underground. Any operation utilizing underground mining for a majority of mill feed is classified as underground. Those operations utilizing entirely surface material for mill feed are classified as surface.

[2]N—nonproducer, P—producer.

newly mined gold is approximately 1,000 to 1,300 mt[4], whereas total world gold stocks stand at a minimum level of 100,000 mt. With new supply representing only about 1 pct of world stocks, production costs of newly mined gold have little influence upon market price relative to movements of the large volume of aboveground stocks. Also, since most new gold goes into jewelry, bullion, and coins, or is held for security reasons, it is not really "consumed" but rather becomes part of the existing stock. As world stocks increase, the effect of stock movements upon price movements increases as well.

[4]The metric ton = 32,150 tr oz.

At the level of individual producing mines, gold production, in general, responds inversely to the market price of gold. However, the production response in the overall industry is composed of two parts. There is the response of current producers and the response of exploration and new mine development. Current producers with the ability to vary the average grade of their mill feed (pay limit) respond to rising gold prices by lowering this cutoff grade or pay limit. Gold output thus falls or remains more or less constant even though mill throughput increases. In this case, higher gold prices enable mines to produce less gold without lowering revenues and extend the life of the mine. Conversely, falling gold prices for these operations will generally result in the cutoff grade being raised (where possible) which raises production, compensates for the lower gold price, and maintains sufficient revenues but could result in a shortening of mine life.

In the case of new mine development, the reaction is different. Rising gold prices will elicit renewed effort at exploration and new mine development. This has been especially true in gold since the dramatic price increases of the mid to late 1970's. The development of a gold mine from deposit discovery to production can take roughly 2 to 10 yr, depending upon a host of technical, financial, and legal factors. The new gold supply that results from rising gold prices is thus temporal in its impact. For example, the high gold prices of 1979–80 resulted in many new mine developments which began producing between 1981 and 1984. To the extent that the current, relatively low, U.S. dollar price of gold causes exploration, new mine development, and expansion plans to be reduced or delayed, the impact upon production will not be evident for a few years because of this time lag.

An examination of recent gold production and price data demonstrates the net effect on world gold production from the interaction of these two responses outlined above. Table 2 contains production data for 1971, 1981, and 1983. From 1971 to 1981, annual gold production from the eight largest MEC producers collectively declined by 9.0 million tr oz. During the same period, the price of gold increased from $41/tr oz to $460/tr oz. South African output declined by 10.2 million tr oz, while the United States, Canada, and Australia posted declines ranging from 81,000 to 570,000 tr oz. Output in other countries (primarily the Soviet Union, China, and Brazil) increased enough to offset around 5.4 million tr oz of this overall decline. The net effect was that total world gold production fell by 5.2 million tr oz between 1971 and 1981.

Most of the South African production decline was due to a lowering of the average mill feed grade (pay limit) and the opening up of newer, lower grade areas as a result of rising gold prices. Since 1981, annual South African production has increased by approximately 762,000 tr oz while the U.S. dollar price of gold has fallen. The price of gold during 1983 averaged around $35/tr oz lower than the average 1981 price and more than $187/tr oz lower if compared to the average 1980 price.

South African and other MEC private sector producers have, where possible, clearly raised their average mill feed grades to compensate for this declining price in order to maintain suffïcent operating revenues. In addition, new mines came into production during the 1979–83 period. In other countries the production responses have been quite different owing to a number of interrelated aspects unique to each country's gold industry; these are dealt with in detail in the individual country sections.

Table 2.—Gold production, 1971, 1981, and 1983 for the 10 largest producing countries, thousand troy ounces

Country	1971	1981	1983	Change 1971–81	Change 1981–83
South Africa	31,389	21,121	21,847	−10,268	+762
Soviet Union	[e]6,700	8,425	8,600	+1,725	+175
Canada	2,243	1,673	2,274	−570	+601
United States	1,495	1,379	1,957	−116	+578
China	[e]50	1,700	1,900	+1,650	+200
Brazil	157	1,200	1,600	+1,043	+400
Australia	672	591	1,035	−81	+444
Philippines	640	758	817	+118	+59
Papua New Guinea	24	553	582	+529	+29
Chile	64	401	571	+337	+170
Total	43,434	37,794	41,183	−5,640	+3,389
8 largest market economy countries[1]	36,684	27,669	30,683	−9,015	+3,014
Total world	46,494	41,250	44,533	−5,244	+3,283

[e]Estimated. [1]Less the Soviet Union and China.

Sources: Lucas (*1*), BuMines (*20*).

Table 3 explains the general relationship evident in some major free world producers between the gold price of a nation's currency, the currency price of gold, and the exchange rate relationship between the U.S. dollar and these other currencies. The relative movements of these variables have a very significant impact upon the grade and quantity of gold ore that is mined and the amount of refined gold that is produced in these countries. The data presented are for the three largest MEC gold producers. An example using Canada will make the paramount importance of these relationships apparent.

In 1978, the U.S. dollar price of gold was $194/tr oz. This meant that Canadian mines needed to produce 4.51 milliounces of gold (0.00451 tr oz) to earn $1 in revenue. This 4.51 milliounces was the "Canadian gold price of the U.S. dollar" in 1978 and dictated the grade and quantity of ore that was mined in Canada. The exchange rate between U.S. and Canadian dollars in 1978 was US $0.88 = Can $1. Thus, the Canadian gold price in 1978 was Can$221/tr oz. Since Canadian primary lode gold production in 1978 was 1.185 million tr oz, Canadian dollar revenues totaled Can$262 million. At the average 1978 exchange rate, this was the equivalent of US$230 million.

In 1980, the average price of gold had risen by 69 pct to an historic high of $612/tr oz. This was the Canadian equivalent of Can$716/tr oz. The impact of the price rise on production was to allow material of much lower grade to be profitably mined. Thus, the "Canadian gold price of the U.S. dollar" also fell 69 pct to 1.39 milliounces for 1980. Canadian lode gold production in 1980 declined to 1.074 million tr oz as a result of lower grade ore being mined. But revenues in terms of both currencies were more than double their 1978 level despite this drop in production.

In 1983, the opposite result was evident. The price of gold fell 31 pct to $425/tr oz. The "Canadian gold price of the U.S. dollar," by definition, increased 37 pct. Production, responding inversely to price, increased 69 pct owing to producing mines increasing the grade of ore mined (where possible) and new mines coming into production as a result of the rising prices of the late 1970's. The overall result was that revenues in U.S. dollar terms increased 18 pct despite the decrease in the gold price. Similarly, Canadian dollar gold revenues rose, but by a larger percent (24) owing to the decline in the value of the Canadian dollar relative to the U.S. dollar.

Table 3.—Relationship between gold price, gold production, and exchange rate variations

Country and currency	Year	Gold per local currency unit, 10³ tr oz	Change from prior period pct	Exchange rate, U.S. dollars per local currency unit	Primary lode gold mine production, 10³ tr oz	Gold market price,[1] local currency per troy ounce	Value or production	
							10^6 local currency unit	10^6 U.S. dollars
United States - dollar ($)	1978	5.15	NAp	1.0	580	$194	$112.5	112.5
	1980	1.63	−68	1.0	636	$612	$389.2	387.2
	1983	2.35	+44	1.0	1,553	$425	$660.0	660.0
Canada - dollar (Can$)	1978	4.51	NAp	.8766	1,185	Can$221	Can$261.8	229.5
	1980	1.39	−69	.8552	1,074	Can$716	Can$769.0	657.6
	1983	1.90	+37	.8114	1,824	Can$524	Can$955.7	775.5
South Africa - rand (R)	1978	5.92	NAp	1.1500	22,700	R169	R3,836.0	4,411
	1980	2.09	−64	1.2854	21,705	R476	R10,331.0	13,279
	1983	2.11	+1	.8991	21,847	R473	R10,333.0	9,290

NAP Not applicable.
[1]Based upon the U.S. dollar average annual price of gold converted at the average annual exchange rate.

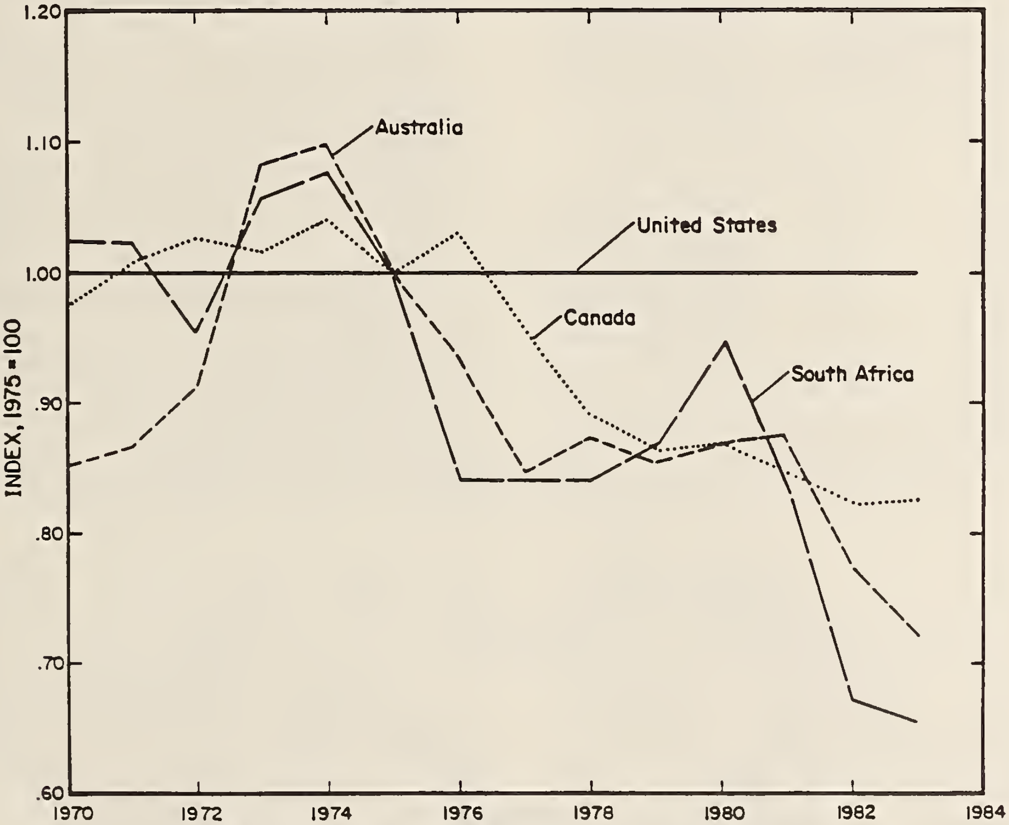

Figure 1.—Index of exchange rates: United States, Canada, Australia, and South Africa.

Variations in exchange rates have significantly impacted industry profitability in recent years. This is because production costs are usually denominated in local currencies, but gold revenues, ultimately, are based upon the international price of gold in terms of the U.S. dollar. If a country's currency declines in value more than the dollar price of gold, the resultant foreign exchange gain can offset both rising production costs and declining prices, albeit not indefinitely. This very important relationship is discussed in detail for South African mines in that country's individual chapter. For now, figure 1 will suffice to underscore the recent history of exchange rate variations for four of the largest MEC gold producers. The figure indexes the current value of each currency relative to its 1975 value. As shown, the currencies of Australia, South Africa, and Canada have declined in value, relative to the U.S. dollar, since 1975. For example, the 1983 South African rand had only 65 pct of the purchasing power of the 1975 rand.

The following summary presents the general results of this study. It provides comparative results of resource and production availabilities, production costs, and future production potential as determined for each nation included in this study. It is intended as a general overview. The gold mining industries of each country vary a great deal owing to many country-specific factors. Indeed, each gold mining industry and each gold mine is absolutely unique. For this reason each major producing country is covered in detail in a subsequent chapter.

HISTORICAL PERSPECTIVE ON PRODUCTION THROUGH 1983

The point of reference of this study is January 1984. This section places the 1984 resource availability and production potential in an historical perspective. The intention is to give a general idea of how much gold had been produced prior to January 1984, and the sources of that production, as well as how much gold is currently being produced from present sources.

Table 4 provides data on the historical production of gold by time period. It is estimated that as of 1984 between 3.8 and 4.0 billion tr oz of gold had been produced throughout history. This is roughly equivalent in volume to a cube 55 ft on a side. Approximately 60 pct of this historical total has been produced in just the last 53 yr with 45 pct of the production during the last 53 yr coming from just one na-

Table 4.—Estimates of total world gold production, by time period

Time period	Total world gold production, 10^6 tr oz	Areas of major production, ranked by size
3900 B.C. – A.D. 1492	400–500	Africa, Europe, Asia.
1493–1600	23	South America, Africa, Europe.
1601–1700	29	Do.
1701–1800	61	South America, Europe, Africa, Mexico.
1801–1900	374	United States, Australia, Soviet Union, South Africa, Asia.
1901–30	585	South Africa, United States, Soviet Union Australia, Canada, Asia.
1931–83	2,286	South Africa, Soviet Union, Canada, United States, Australia.
Total (rounded)	3,800–4,000	NAp.

NAp Not applicable.

Sources: Mohide (*4*) and the authors' own estimates based upon numerous other sources.

Table 5.—Estimated total production for five major historic gold-producing countries[1]

Country	First major discoveries	Total production 10^6 tr oz	Relative reliability of estimate
South Africa	1872	1,247	Good.
Soviet Union	1775	350–450	Poor.
United States	1799	335	Good.
Canada	1866	215	Do.
Australia	1851	190	Do.

[1]Compiled from numerous sources and authors' own estimates.

Table 6.—World gold production in 1983[1]

Country	1983 gold production, 10^3 tr oz	1983 ranking
Major countries (discussed in detail):		
South Africa	21,847	1
Soviet Union	8,600	2
Canada	2,274	3
United States	1,957	4
Brazil	1,600	6
Australia	1,035	7
Subtotal (84 pct of total)	37,313	NAp
Important countries (general discussion):		
China[1]	1,900	5
Philippines	817	8
Papua New Guinea	582	9
Chile	571	10
Zimbabwe	430	11
Colombia	429	12
Dominican Republic	348	13
Ghana	303	14
Peru	166	15
Mexico	223	16
Subtotal (13 pct of total)	5,339	NAp
40 other countries (not discussed) (3 pct of total)	1,881	NAp
Total (100 pct)	44,533	NAp

NAp Not applicable.
[1]Not discussed owing to a lack of information on gold resources.

Sources: Lucas (*1*), BuMines (*20*).

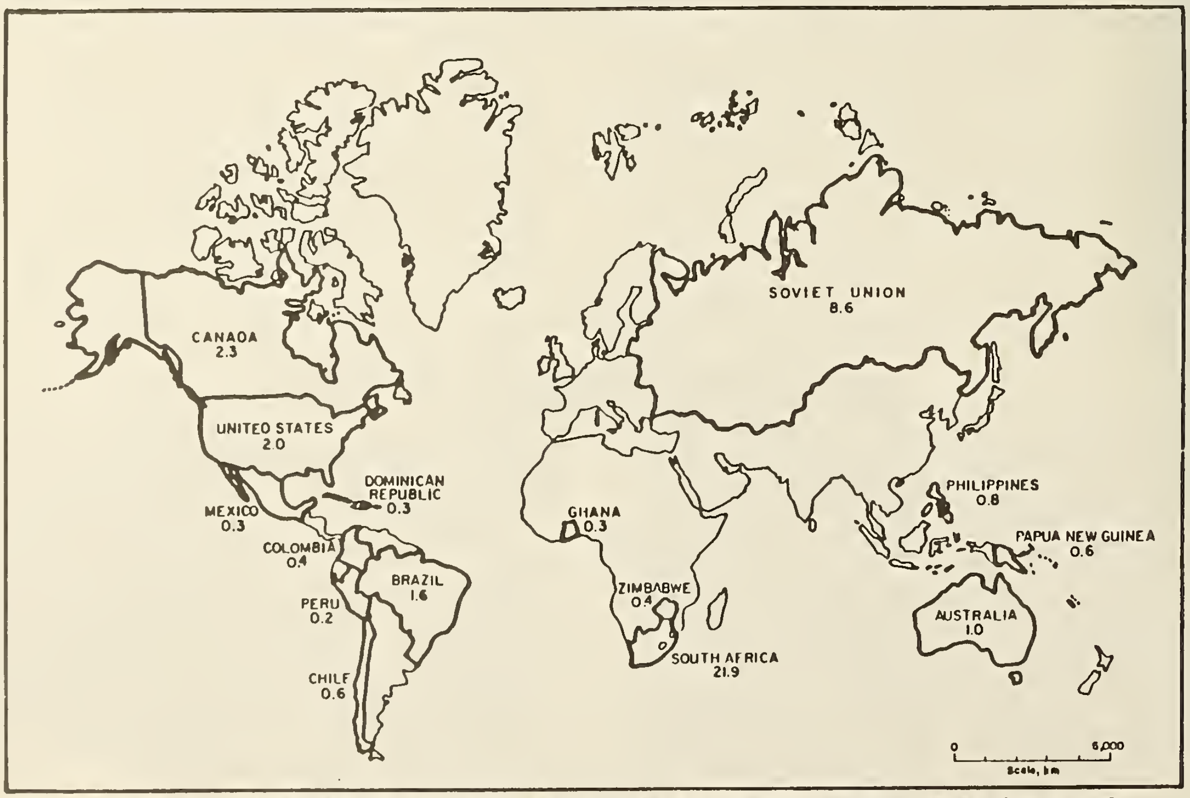

Figure 2.—Evaluated gold producing countries and 1983 production levels (10^6 tr oz).

tion, the Republic of South Africa. This is why *the* issue of world gold availability (especially MEC gold availability) centers on the ability of South Africa to maintain its enormous productive capacity.

The Soviet Union has not released any production data since 1934, when it began a policy of treating all such data as state secrets. Estimates, not surprisingly, have shown wide variation over the years. A reasonable estimate of Soviet Union gold production since 1930 would be between 250 and 350 million tr oz. This means that the Soviet Union and South Africa not only account for 75 pct of current world production but have also accounted for 55 to 60 pct of total production since 1930. World gold production should remain dominated by these two nations for the remainder of the 20th century.

Table 5 summarizes historical production for the five countries that have accounted for a majority of world gold production since 1930 and places a reliability estimate on the total production figures. Table 6 provides a breakdown of 1983 world production. Figure 2 shows the 15 countries discussed in this study and their 1983 production amounts. They represent 15 of the top 16 world gold producing countries; China is omitted owing to lack of information.

As shown in table 6, the six nations discussed in detail in this study accounted for 84 pct of 1983 world gold production. The People's Republic of China (ranked fifth) is not discussed at all owing to a lack of information on gold resources. The five MEC's evaluated in detail similarly account for 84 pct of MEC production.

RESOURCE OVERVIEW, 1984

Demonstrated resource tonnages and weighted average grades were determined for all 135 primary gold properties (table 1) in the 14 market economy countries that were included in the cost evaluations. This overview concerns itself primarily with a subset of 111 operations that were either known producers as of 1984 or major operations in the late stages of development that appeared certain to come into production during 1984–86. This latter group consists of only four properties: the McLaughlin operation in California, United States, and the Golden Giant, Lac Minerals, and Teck-Corona operations in the Hemlo District of Ontario, Canada. The 107 major operations producing in 1984 easily account for over 90 pct of primary gold production and over 80 pct of total primary plus byproduct production in the MEC's. The excluded properties are 16 Alaskan operations of intermittent or questionable production status, 6 nonproducing properties in the continental United States, 1 nonproducing property in Canada, and 1 nonproducing property in Mexico. Cost and availability estimates for these 24 nonproducing properties are discussed in the individual country chapters.

Table 7 and figure 3 provide summary data, by country, of total 1984 demonstrated gold resources in the 111 selected properties. The estimates on the left side pie of figure 3 are presented on a contained basis; that is, the total amount of gold contained in the mill feed. This measure accounts for mining recovery and dilution. As is clearly evident, the vast majority of gold on a contained basis is ac-

Table 7.—Total demonstrated primary gold resources in 111 selected properties in market economy countries as of January 1984

Country	Total contained gold, 10^6 tr oz	Total recoverable gold	
		10^6 tr oz	Pct of total
South Africa	758.0	716.0	87
United States[1]	40.4	32.2	4
Canada[1]	38.4	36.6	4.5
Brazil	10.5	9.8	1
Ghana	7.3	6.0	<1
Australia	6.7	6.4	<1
Philippines	4.1	3.5	<1
Zimbabwe	3.7	3.0	<1
Chile	2.4	2.0	<1
Bolivia and Colombia	1.0	.8	<1
Taiwan	.5	.4	<1
Total	873	819	100

[1]Estimates differ from totals given in country sections owing to the exclusion of certain nonproducing properties.

NOTE.—Data may not add to totals shown because of independent rounding.

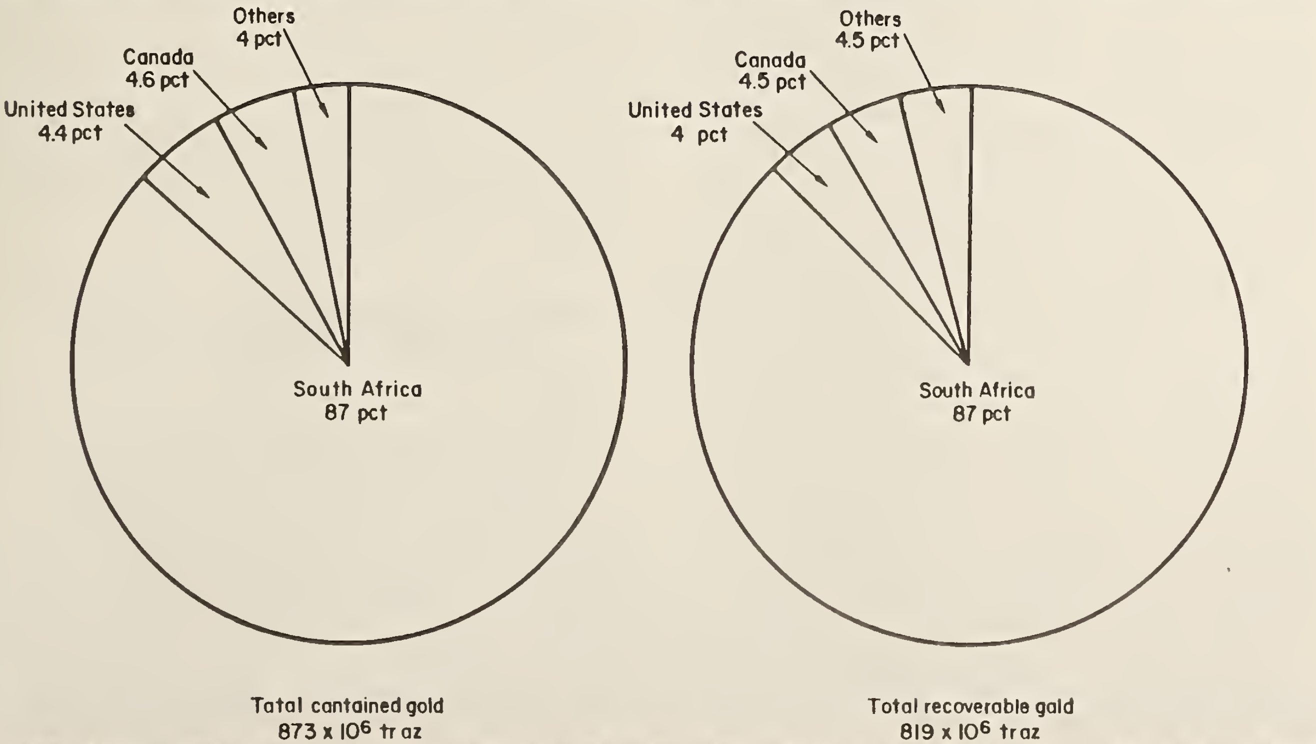

Figure 3.—Percentage distribution by country of total contained and total recoverable gold in 111 selected properties.

counted for by just three countries, the Republic of South Africa, the United States, and Canada. South Africa alone accounts for 87 pct of the total contained gold. The domination of these three countries is due to two factors. First, the Witwatersrand Basin of South Africa is the single largest source of gold the world has ever known. Second, Canada and the United States have benefitted from ongoing exploration and development activity due to their having large established mining industries with abundant technical expertise and sufficient financial capital. These countries also have histories of political and economic stability. Australia accounts for just under 1 pct of total contained gold and has the same historically strong mining industrial base as Canada, the United States, and South Africa. This nation has added significantly to its demonstrated resources in recent years and has good potential for further additions as exploration and development activity continues.

There are two caveats to the above resource analysis which must be made to place world gold resources in the proper perspective. They concern the type of resource data that are reported, and the type of resource occurrence that accounts for production in an individual country.

First, the information reported often varies owing to Government policies and also to a reluctance on the part of many mining companies to divulge data on their gold operations. This is due to a number of factors. Among them is the desire to minimize or avoid taxation in countries that tax the value of unmined gold reserves. Also, most publicly held mining companies are required to report their reserves (as opposed to resources) annually to various institutions. For valid reasons, these annual reported reserves are usually defined as that ore which has been developed on at least three sides and assayed as thoroughly as required. These "proven reserves" are redefined each year based on production, new development, new assays, changes in prices and costs, and, possibly, changes in technology. These proven reserves are justifiably conservative for the above reasons and because many vein-type gold mines are geologically erratic, which makes reasonable inferences of resources difficult or perhaps impossible. Also, exploration work to delineate resources is a costly and time consuming endeavor and will not be done by small operators or poor countries, or perhaps even by large operators that have been in production for a long time. For example, some mines in Canada have annually reported proven reserves sufficient for only 1 to 5 yr of production and have been doing so for 20 yr or longer. Most gold mining operations will not estimate beyond the proven reserve level without a very good reason, such as plans for major capital investments.

The second caveat deals with the type of resource occurrence in an area or country. Some countries, such as Brazil, Colombia, Bolivia, and the U.S. State of Alaska, derive the great majority of their gold production from placer deposits. These operations are generally small scale, intermittent, and nearly impossible in most cases to estimate for contained resources, much less costs of production. In the case of Brazil, especially, most production emanates from tens of thousands of individuals or small groups mining placer deposits in the Amazon Basin. The Government of Brazil does not really know how much gold is produced or smuggled out of the country. Brazil undoubtedly has large gold resources, but attempting to measure them is virtually impossible.

Thus, there are two forces at work in terms of demonstrated resource estimation. First, the largest and best established areas generally have the best estimation and reporting. Second, those countries or areas with geological occurrences that lend themselves relatively easily to estimation, such as the Witwatersrand Basin, have the best available data in terms of quality and quantity. In the case of the South African mining industry, the quality and quantity of reported data are unsurpassed. Basically, the key to ascertaining *world* demonstrated gold resources is to know where gold has *not* been measured or reported in addition to knowing where it has been measured and reported. This study, by necessity, deals only with countries and areas where enough basic information is collected and reported so that it is possible to estimate demonstrated resources with some reasonable degree of confidence. In that sense, the demonstrated resource estimates of this study must be considered conservative.

TOTAL PRIMARY GOLD AVAILABILITY AND PRODUCTION COST EVALUATION

The same subset of 111 operations were evaluated to determine relative long-term production costs and total gold availability. Figure 4 and supporting data in table 8 summarize the overall results of this evaluation. This figure and table relate cumulative gold availability to increasing production cost levels. In addition, table 7 relates total gold availability by nation, and the right side of figure 3 relates total gold availability by national percentage contributions.

The major conclusions of the total availability evaluation follow:

1. South Africa is by far the single largest source of economic gold production. It represents 716 million tr oz (87 pct) of the 810 million tr oz of total recoverable gold available from these 111 operations.
2. 70 pct of total recoverable gold is economic at a cost level of $300/tr oz or less. This gold is available from just 46 operations, 23 of which are in South Africa. South African mines account for 90 pct of the gold in this cost range.
3. 83 pct of total gold is available at a cost level of $400/tr oz or less. This additional 13 pct is contained within another 25 operations. South African mines also account for 90 pct of total gold available at $400/tr oz or less.
4. The great majority (94 pct) of recoverable gold available from the evaluated demonstrated resources is contained within ore bodies mined by underground methods. The individual country percentages South Africa, 98 pct of gold available from underground resources; Canada, 91 pct; Australia, 77 pct; United States, 17 pct.

COMPARATIVE PRODUCTION COSTS IN MAJOR PRODUCING COUNTRIES

Table 9 and figure 5 contain comparative long-run cost data for South Africa, Canada, the United States, and Australia. A general comparision of production costs reveals that capital costs per ounce of recovered gold are similar among the four countries. For underground resources, the weighted average estimates for capital costs range from $52/tr oz to $73/tr oz recovered gold. Surface mining capital costs in the United States and Australia are effectively the same at $47/tr oz and $48/tr oz, recovered gold, respectively. Total capital costs are obviously much greater for underground operations because of the need for such high-cost items as shaft systems and mine plant facilities plus more expensive exploration requirements. However, owing

Table 8.—Supporting data for figure 4: distribution of total recoverable gold by cost level and country

Break-even cost or price level[1]	Number of operations (cumulative)	Total recoverable gold, 10^6 tr oz (cumulative)	Cumulative percent of total availability	Countries within indicated range, ranked by amount of recoverable gold
$200 or less	14	184.5	22	$200 or less: South Africa, Canada, Brazil, United States, Dominican Republic.
$300 or less	46	576.4	70	$201 to $300: South Africa, Canada, United States, Australia, Philippines, Zimbabwe, Chile, Bolivia.
$400 or less	71	667.6	83	$301 to $400: South Africa, Canada, United States, Australia, Brazil, Zimbabwe, Colombia.
$500 or less	96	773.1	94	$401 to $500: South Africa, Canada, United States, Philippines, Australia, Zimbabwe.
$600 or less	105	811.8	99	$501 to $600: South Africa, Zimbabwe, Canada, United States.
$700 or less	107	812.5	99	$601 to $700: Canada, Zimbabwe.
Over $700	111	819.0	100	Over $700: Ghana, Taiwan.

[1]The break-even cost or price level is that point where long-run total production cost per ounce = required price per ounce to obtain a 0-pct discounted cash flow rate of return (DCFROR).

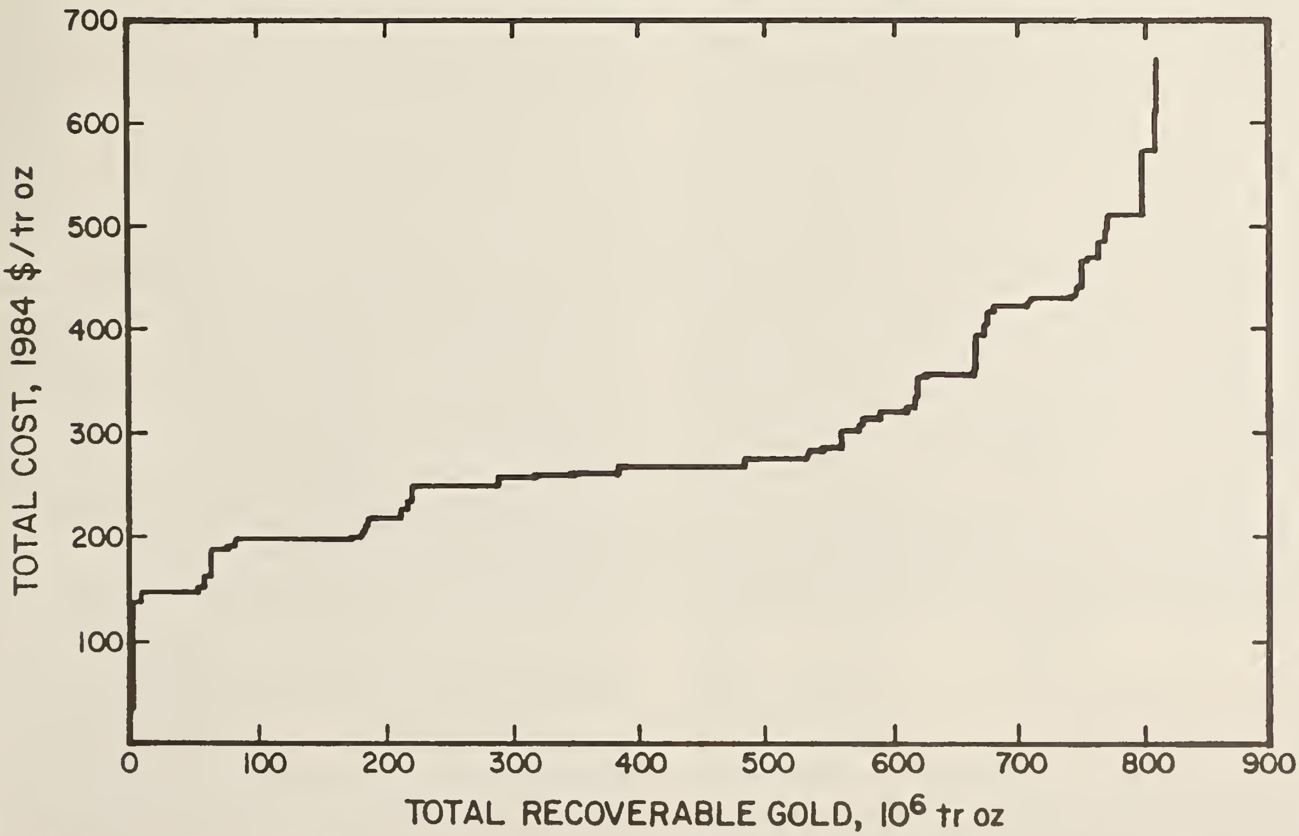

Figure 4.—Potential gold available at break-even costs of production from 111 operations in market economy countries as of January 1984.

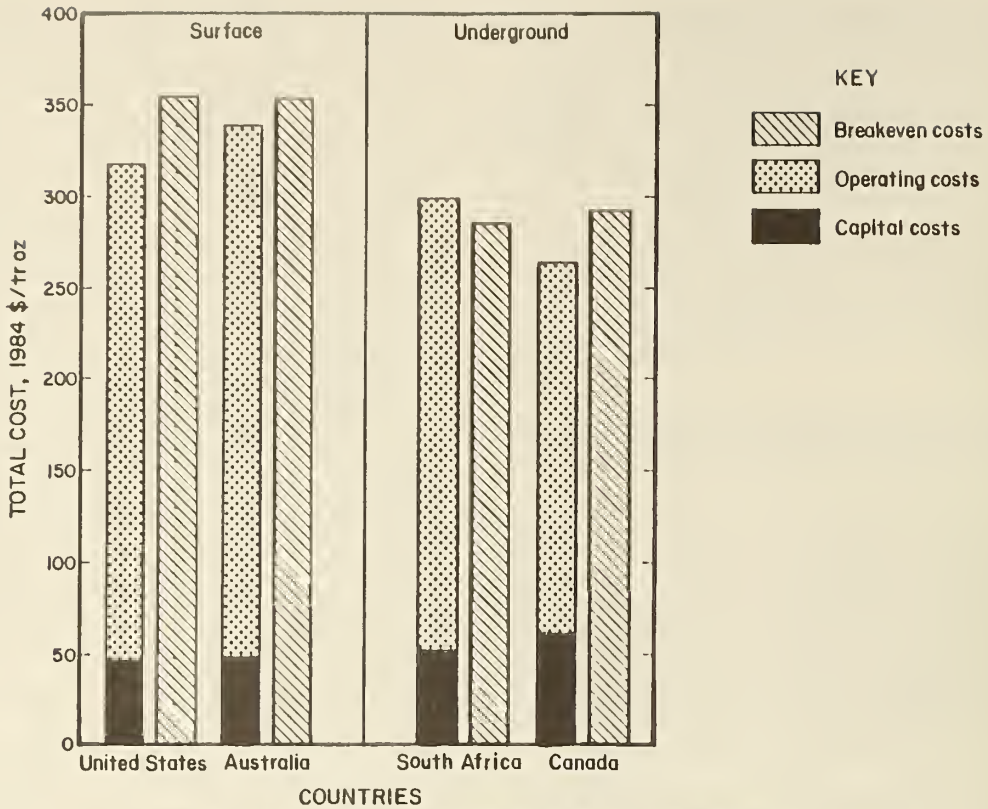

Figure 5.—Comparative long-term total production costs in selected countries.

Table 9.—Comparative long-run total gold production costs in selected major producing countries

Country	Resource occurrence	Capital cost per troy ounce[1]		Operating cost per troy ounce[2]		Total capital plus operating cost per troy ounce		Break-even cost or price level[3]	
		Range	Weighted average	Range	Weighted average	Range	Weighted average	Range	Weighted average
South Africa	Underground	$7-$95	$52	$123-$488	$247	$145-$559	$299	$148-$573	[4]$285
United States[5]	Surface	21-126	47	117- 401	271	152- 527	318	173- 538	354
Canada[6]	Underground	22-136	62	93- 526	202	134- 598	264	134- 598	292
Australia	Underground	44-132	73	148- 314	222	192- 444	295	200- 477	310
	Surface	NAp	48	240- 310	291	290- 360	339	325- 365	353

NAp Not applicable.
[1]Unrecovered capital investment in mine and and mill plant and equipment, infrastructure, and development remaining as of Jan. 1984 and reinvestments through life of operation.
[2]Total mining plus milling cost per troy ounce of recovered gold.
[3]The break-even cost or price level is that point where long-run total production cost per ounce = required price per ounce at 0-pct DCFROR.
[4]The break-even cost estimate is lower than the total capital plus operating cost estimate owing to the influence of byproduct credits for uranium.
[5]Underground cost data for the 1 mine in this category were withheld to avoid disclosing possible proprietary data.
[6]Includes 3 Hemlo District operations currently in late stages of development, which will be among the lowest cost world producers and represent 44 pct of total recoverable gold analyzed in Canada. Surface mining is insignificant.

to higher grades, the capital costs on a per ounce basis at underground mines represent only a small part of total production costs.

Long-run operating costs[5] (mining plus processing) per ounce of recovered gold actually favor underground mining in general. This is due again to generally higher grades and higher mill recoveries at underground mines. In the case of South Africa, the weighted-average cost estimates are dominated by a number of very large mines which have excellent scale economies. For Canada, the overall estimate is dominated by the 3 new mines in the Hemlo District, which will rank among the 10 lowest gold mines in the world.

It is important to stress that this analysis is comparing long-run total production costs per ounce of recovered gold. If one looks only at direct operating costs or current total production costs, the results of this type of comparison would possibly be different, but from a long-term availability perspective, which is cognizant of current and future capital and operating costs and which expresses those costs on a recovered-gold basis, the results favor underground mining.

A final comparison of long-run break-even total production costs demonstrates that all four of these major gold producing MEC's have, on average, gold mining industries that are economic at long-run prices similar to those that have prevailed in recent years. However, if prices remain indefinitely below \$350/tr oz to \$400/tr oz many individual mines and new mine developments will become uneconomic.

POTENTIAL ANNUAL PRODUCTION THROUGH 2000

This section is intended to provide a general overview of annual production potential for the 111 evaluated primary operations relative to production cost levels and country distribution. The individual country chapters provide general assessments of the production potential of each nation through the end of this century. These chapters deal with all sources of gold production, including byproduct production from base metal mines. A number of country-specific issues that will undoubtedly impact upon each nation's future production potential (primary and byproduct) are also dealt with separately in the individual country chapters.

Figure 6 plots annual production potential through the year 2000 at increasing cost levels. The major conclusions of the analysis are—

1. Total gold production from the 111 evaluated operations is not expected to decline significantly during the remainder of this century even with no major additions to demonstrated resources. Production in the year 2000 is expected to be only 9 pct below the level for 1984, given constant 1984 prices exceeding \$300/tr oz, owing primarily to a maintenance of production by South African mines. This assumes that market forces are the only factors at play. Clearly, political, social, or military turmoil could greatly change this scenario.

2. In any given year, it is expected that more than 80 pct of total production will emanate from operations with long-run total production costs of \$400/tr oz or less.

3. Because of the relative importance of surface mines in the United States and Australia, both countries must continuously replace a portion of their demonstrated resource base to maintain current primary gold production levels. Current demonstrated resources at most mines are sufficient for only 5 to 10 yr of production. Both nations have experienced tremendous exploration and development activity in recent years, which has served to increase annual output. Over the long term, however, the main issue will be one of production maintenance rather than production enlargement. Exploration, development, and production economics in these two nations have come to favor production maintenance by surface minable resources.

4. Canadian primary gold production potential through the turn of the century should also remain relatively constant due to the development of the Hemlo gold district. This district is expected to increase annual output by at least 700,000 tr oz/yr by the end of the 1980's, which would offset projected declines from other mines. The three mines have initial demonstrated resources sufficient for at least 20 yr of production at full capacity, beginning in 1986.

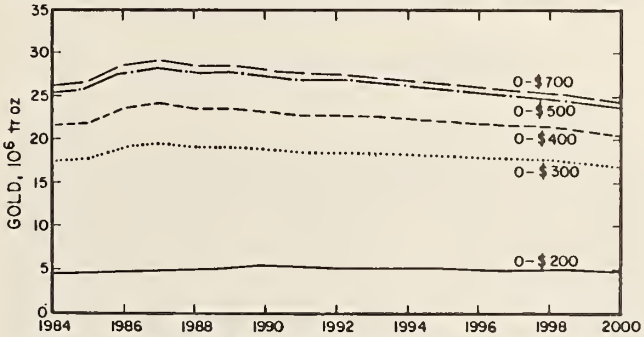

Figure 6.—Potential annual gold production to the year 2000 from 111 primary operations.

Figure 7 continues this discussion by plotting potential annual output through the year 2025. The major point to be made is that total annual gold production may decline very rapidly after the turn of the century unless major new discoveries are made and new mine development continues. A discussion of the potential for new discoveries of major goldfields is beyond the scope of this study, but it is clear that new demonstrated resources must be added to replace the eventual depletion of the Witwatersrand Basin of South Africa during the next 30 yr, or world gold production may decline very significantly. To replace a projected decline in South African output of 7.6 million tr oz/yr during 1990–2010 would require the development of at least 26 mines with annual production capacities of 290,000 tr oz/yr (the size of the Golden Giant Mine at Hemlo) or the development of at least 45 mines with annual production capacities of 170,000 tr oz/yr (the size of the new El Indio Mine in Chile). This, clearly, is *the* challenge facing the MEC gold mining industry.

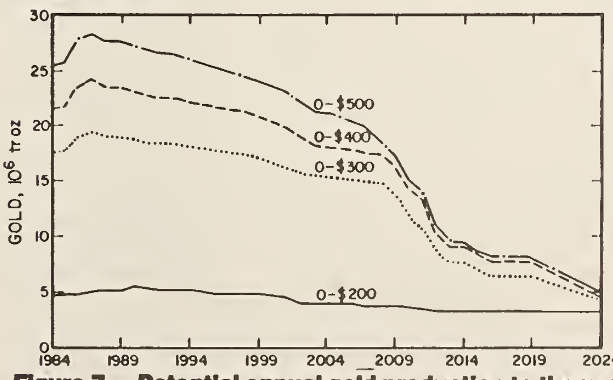

Figure 7.—Potential annual gold production to the year 2025 from 111 primary operations.

[5]The appendix contains the definition of operating costs as employed in this study.

REPUBLIC OF SOUTH AFRICA

It is estimated that roughly 40 pct of all the gold ever mined in the MEC's has been produced by South African operations. There is continued concern that this immense productive capacity will begin to decline soon, causing a reduction not only in world gold supply but also in the ability of the MEC's to exert the major influence upon the world gold market.

To address the current and future importance and potential of South African mines, it is necessary to place historical production and economic developments into perspective. In so doing, the current 1984 "snapshot" of the industry is placed in its proper perspective and a more precise indication of future production potential is possible.

HISTORICAL PERSPECTIVE

Of the five countries that have produced the majority of the gold mined throughout history (South Africa, the Soviet Union, the United States, Canada, and Australia), South Africa's gold mining industry is the youngest. Gold was first discovered in 1872 at Pilgrim's Rest in the Eastern Transvaal. Two other major discoveries were made in the Eastern Transvaal at Kaapsche Hoop in 1874 and at Barberton in the early 1880's. Production of gold in South Africa did not reach a large scale until the discovery of the Witwatersrand Basin gold deposits in the mid-1880's. Two landmarks in the history of Witwatersrand Basin gold mining occurred in 1885, when the first crushing of conglomeritic gold ore occurred, and in 1886, when the Main Reef Leader was found and tested by George Walker and George Harrison (*5*, p. 39).[6] These developments are typically referred to as the official start of gold production from the Witwatersrand Basin gold deposits. From 1886 onward, the Witwatersrand Basin gold deposits have accounted for the vast majority of South African gold production and have proven to be the largest single source of gold the world has ever known.

From 1886 to 1930, exploration and production in the Witwatersrand Basin concentrated on the Central, East, and West Rand areas (fig. 8), in an arc from the city of Randfontein, 30 km northwest of Johannesburg, to the city of Nigel, 50 km southeast of Johannesburg. During this period, there was some cursory exploration and production from other areas as far west as the vicinity of Klerksdorp, but the activity was sporadic and on a small scale (*5*, p. 39).

In 1932, the Republic of South Africa went off the official world gold standard. This economic move provided a major incentive for renewed exploration for gold in the Witwatersrand Basin. In addition, a technologic advance occurred in 1934 with one of the first uses of a magnetometer to discover gold-bearing reefs on the West Wits Line, also referred to as the Far West Rand, located southwest of Randfontein. At about the same time, the discovery of the Vaal Reefs Mine in the Klerksdorp area rejuvenated gold production in that particular goldfield (fig. 9).

It was not until the late 1940's and early 1950's that the Orange Free State Goldfield was discovered and development began. The last of the major goldfields to be brought into production in the Witwatersrand Basin was

[6]Italicized numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

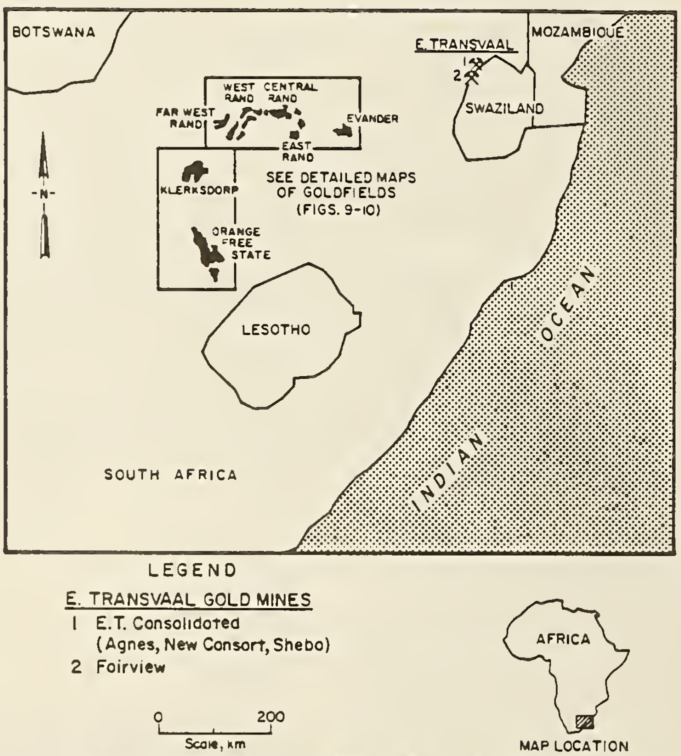

Figure 8.—Goldfields of the Witwatersrand Basin, South Africa.

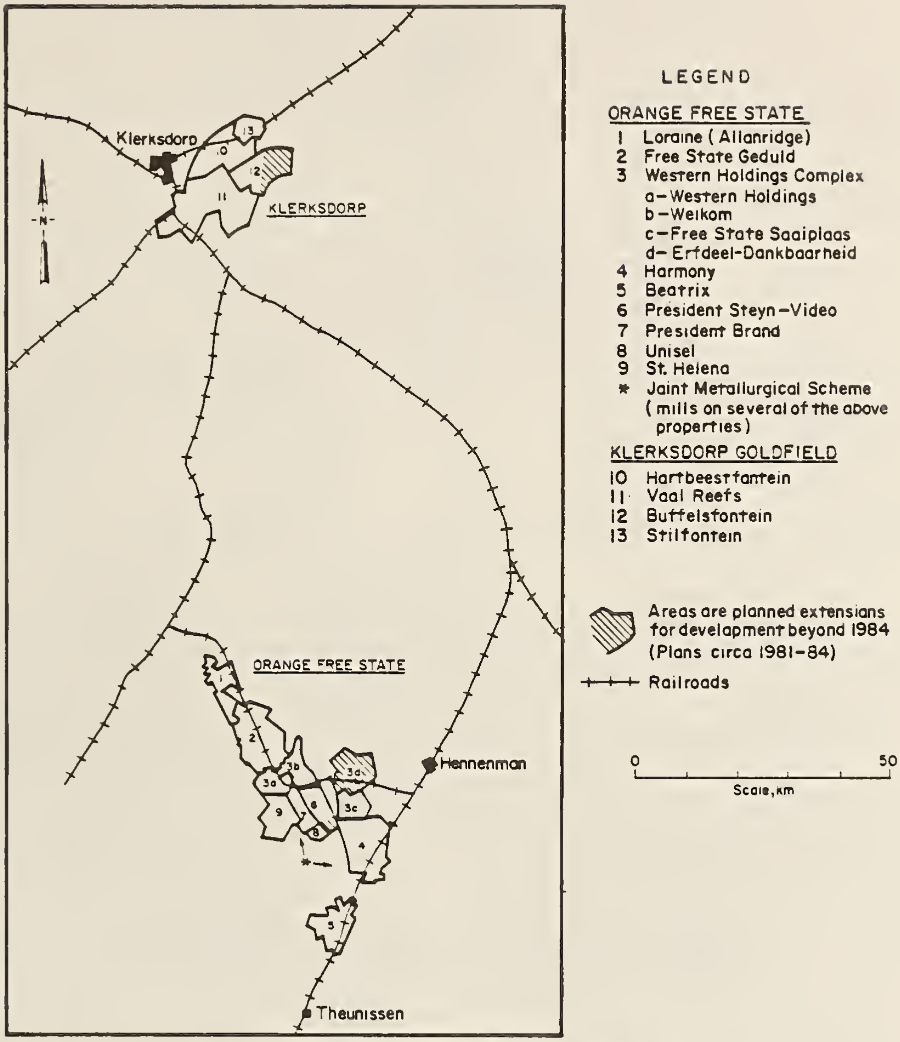

Figure 9.—Gold mining operations of the Orange Free State and Klerksdorp Goldfields.

the Evander Goldfield, about 110 km southeast of Johannesburg, which was discovered and developed in the late 1950's and early 1960's (fig. 10). All new gold production since the mid-1960's has come from the development of down-dip or on-strike extensions of reefs being mined or from the mining of additional reefs on lease areas covered by the existing operations.

Figure 11 shows annual gold ore and refined gold production in South Africa from 1970 through 1983. Table 10 contains data on average annual gold ore and refined gold production for each 5-yr periods from 1885 through 1979 and annually from 1980 through 1983. Over this 99-yr history of gold production, South Africa has produced about 1.247 billion tr oz gold from the milling of about 4.062 billion mt ore, which gives an indicated recoverable gold grade for the entire 99-yr period of 9.5 g/mt milled. This total production of 1.247 billion tr oz probably represents about 40 pct of all gold ever produced in the MEC's, and it is most likely that at least 95 pct of South Africa's production has come from Witwatersrand Basin gold deposits.

In the 99-yr history of gold production in South Africa, 43.2 pct of total gold production came in the first 70 yr and 56.8 pct in the period 1955–83. The recoverable gold grade for the first 70 yr was about 9.1 g/mt ore milled, compared with 9.9 g/mt ore milled for 1955–83. This increase was primarily due to the high-grade Orange Free State mines, which were brought into production in the early 1950's.

Average annual production of gold remained fairly stable in South Africa from 1910 through 1954. Average annual gold production for the 5-yr periods during this time ranged from 8.4 million tr oz during 1920–24 to 13.5 million tr oz for 1940–44. It was only in 1955–70 that gold production in South Africa soared, with the average annual gold production for the 5-yr periods increasing from 12 million tr oz during 1950–54 to 30.8 million tr oz for 1965–69. This increase was mostly due to the milling of higher grade ore, although the average annual milled ore tonnage also increased from about 57 million mt in 1950–54 to nearly 75 million mt for 1965–69. The increase in the grade of ore milled is shown by the near doubling of the indicated recoverable gold grade from 6.6 g/mt milled during 1950–54 to 12.8 g/mt milled during 1965–69. Again, the major factor in this increase was the discovery and development of the high-grade Orange Free State deposits.

Another factor was the profitability squeeze due to rising working costs and a static gold price. This caused the mines to increase the average grade of mill feed. This squeeze was alleviated by freeing the price of gold complete-

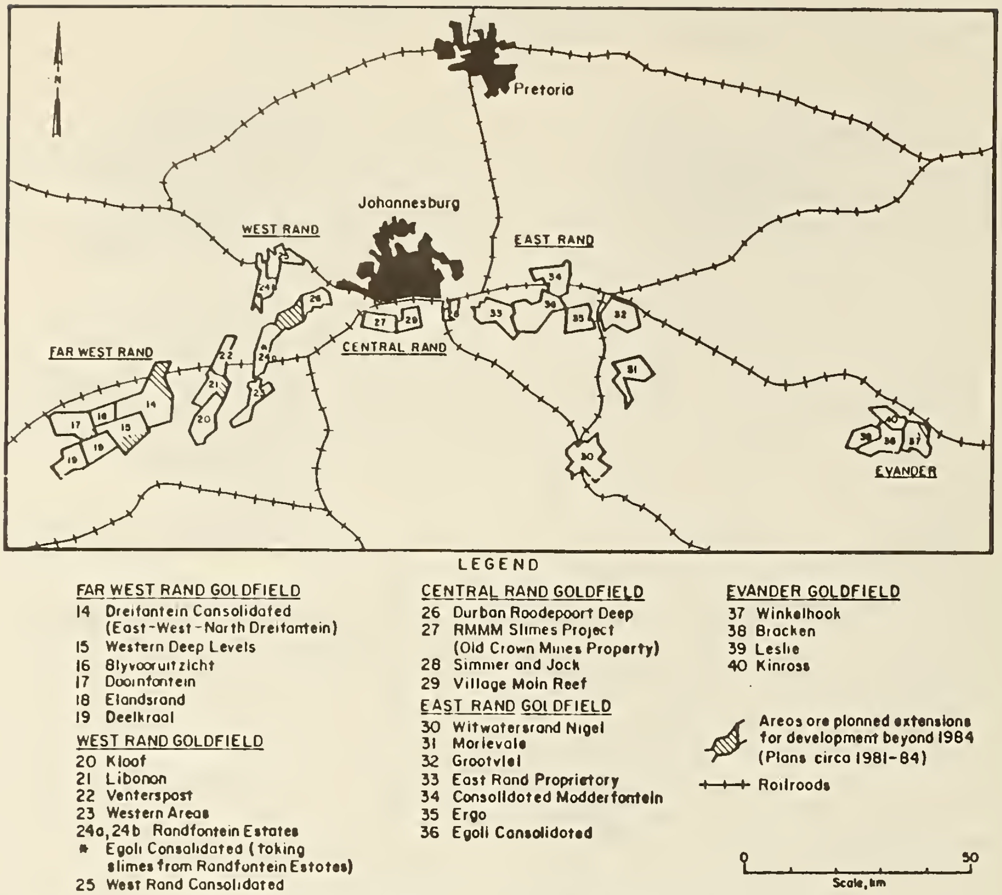

Figure 10.—Gold mining operations of the Far West Rand, West Rand, Central Rand, East Rand, and Evander Goldfields.

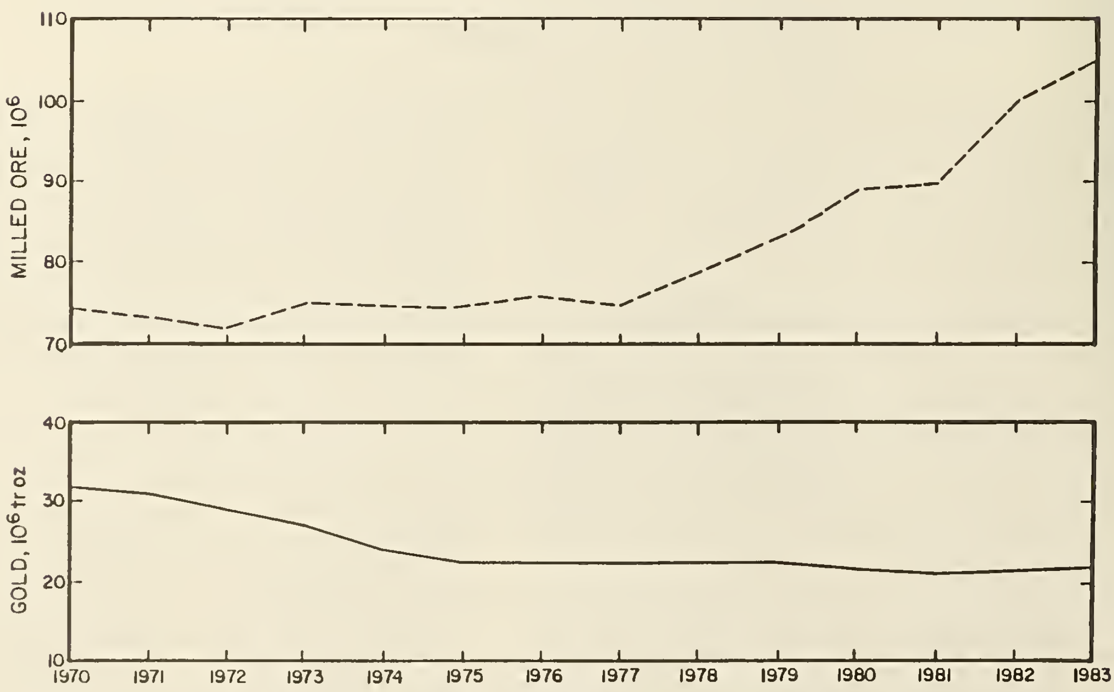

Figure 11.—Gold ore and refined gold production in South Africa, 1970–83.

Table 10.—South African gold ore and gold production, 1885–1983

Time period	Total production during 5-yr period		Average annual production during year or period		Indicated average annual recovery grade, g/mt
	Ore milled, 10^3 mt	Gold produced, 10^3 tr oz	Ore milled, 10^3 mt	Gold produced, 10^3 tr oz	
1885–89	NA	631	NA	126	NA
1890–94	NA	5,293	NA	1,059	NA
1895–99	24,280	14,248	4,856	2,850	18.2
1900–04	NA	9,068	NA	1,814	NA
1905–09	71,664	31,508	14,333	6,302	13.7
1910–14	114,914	42,086	22,983	8,417	11.4
1915–19	124,422	44,162	24,884	8,832	11.0
1920–24	113,831	42,021	22,766	8,404	11.5
1925–29	138,600	50,441	27,720	10,088	11.3
1930–34	163,156	54,046	32,631	10,929	10.4
1935–39	241,980	58,828	48,396	11,766	7.5
1940–44	301,227	67,665	60,245	13,533	7.0
1945–49	266,853	58,642	53,371	11,728	6.8
1950–54	284,194	60,147	56,839	12,029	6.6
1955–59	317,131	85,251	63,426	17,050	8.4
1960–64	356,968	126,360	71,394	25,272	11.0
1965–69	374,429	154,342	74,886	30,868	12.8
1970–74[1]	383,887	144,681	76,777	28,936	11.7
1975–79	398,970	113,641	79,794	22,728	8.8
1980	NAp	NAP	89,915	21,704	7.5
1981	NAP	NAp	90,000	20,446	7.0
1982	NAp	NAp	100,000	21,348	6.6
1983	NAp	NAp	105,000	21,863	6.5
Total or average	4,062,000	1,247,258	41,025	12,604	9.5

NA Not available. NAp Not applicable. [1]Last period of no slimes reprocessing.

Source: Reference 6

ly in the early 1970's. This development led to two trends during the 1970's at South African gold operations. First, the higher level of prices allowed the mill feed grades to be lowered to attain the same or higher level of revenues. Second, the higher prices led to reevaluations of the economics both of low-grade underground resources and of retreating low-grade tailings dumps for gold and uranium recovery. Thus, by 1975–79, the average recoverable gold grade had decreased from 12.8 g/mt milled in 1965–69 to about 8.8 g/mt milled. This recoverable grade was still about 33 pct higher than the recoverable gold grade being experienced in 1950–54.

As a first point of reference for the discussion that follows, 21.8 million tr oz gold was produced from 105 million mt ore milled in 1983, for an indicated recovery grade of 6.5 g/mt. These data do not include any of the major operations that produce gold solely from the retreatment of low-grade sand and slimes dumps but do include the 38 major operations producing gold primarily from underground mining plus several smaller underground operations that are not members of the Chamber of Mines.

As a second point of reference, this study estimates that as of January 1984, a total demonstrated resource of 5 billion mt material is available for milling at 38 primarily underground operations and 6 entirely surface dump retreatment operations. This 5 billion mt of demonstrated resource contains an estimated 716 million tr oz recoverable gold at an estimated overall recovery grade of 4.4 g/mt milled. Comparatively, for the 99 yr from 1885 through 1983, 4.062 billion mt ore was milled to produce 1.247 billion tr oz gold at an indicated recovery grade of 9.5 g/mt. Thus, as of 1984, about 57 pct as much gold as was produced in South Africa over the last 99 yr should still be available for future production from about 125 pct as much total feed material. The overall recoverable gold grade of 7.3 g/mt for the remaining underground resource as of 1984 is about 25 pct less than the historical recoverable gold grades.

RESOURCE OVERVIEW, 1984

In South Africa, the Chamber of Mines, the mining houses, and individual companies provide detailed information on an annual and quarterly basis. The major complications in South African gold "reserve" assessments occur because a typical Witwatersrand gold mine makes regular assessments of four different categories of available tonnages and grades. The four categories, with definitions paraphrased from reference (7) follow:

Proved reserve — This is the material tonnage and grade that are reported in the annual reports. In reliability and availability this is the highest of the three "reserve" categories in that the ore has been fully exposed by development and/or stoping and has been blocked out and sampled. If not immediately ready for mining, it will be available within 6 months to a year, at most.

Probable reserve — This material is that contained within a zone of mineralization to which the sampling values of the proved reserve are believed to apply, although with less certainty. The extent of this zone is fixed arbitrarily from local knowledge and experience, using the sampling results from any boreholes that have penetrated the zone. This tonnage is termed the probable and "partly proved" reserve.

Possible reserve — Also known as prospective ore, this is material that is an extension of the ore body or is a new ore body that is beyond the zones of the proved and probable reserves. Its estimated tonnage and value are less certain as sampling information is meager. In the case of new, undeveloped, and deep gold mines, the possible reserve is assessed from deep borings put down on the strength of the geophysical prospecting program. The proved and probable categories mentioned above will only be figured later as development opens up the new mine underground.

Life-of-mine-reserves — This is an estimate of the total tonnage of ore in the mine, both payable and unpayable, and basically represents the summation of the three categories described above. This estimate forms the basis of all detailed long-term forecasts (more than 5 yr into the future), which are required periodically for determination of development schemes at producing operations and at undeveloped mines.

The life-of-mine-reserves category measures the long-term potential of a South African gold mine in the Witwatersrand Basin. It is the category estimated in this study. There are several ways to estimate this tonnage, and all are described very well in Storrar's book (7). The methods

Table 11.—1984 demonstrated gold resources in South Africa and comparison to past production

Resource	Millable material, 10^6 mt	Weighted-average gold grade, g/mt		Contained gold, 10^6 tr oz	Recoverable gold, 10^6 tr oz
		Mill feed	Recoverable		
1885–1983, underground	4,061	10.0	9.5	1,306	1,247
1984 demonstrated:					
Underground[1]	2,988	7.7	7.3	739	702
Surface[2]	2,077	.29	.21	19	14
Total or average	5,065	4.7	4.4	758	716

[1]Contained in 38 major underground mining operations.
[2]Represents tailings material being reprocessed at 10 major underground operations as part of their overall production plus 6 solely surface reprocessing operations.

vary basically in the mathematical and statistical techniques used. All of the methods must include a detailed plan view of the mine and adjacent properties, some cross-sectional plans, and as much historical data on past and present development results, borehole samplings, and ore production as possible. With these data, the probable area, mining width, and grade over the mining width are carefully examined, and an assessment is made of the total tonnage and value of the ore in the mine.

The life-of-mine reserve assessments made in this study are based solely on publicly available data, most of them from the annual reports of the mining companies. The type of detailed data and factors that would be available to the mining company owning the property were not accessible for this study. Still, it is felt that the estimates should be within ±25 pct of actual tonnages and grades that will result from mining. These results, in many cases, will not be known until well into the 21st century and could be significantly affected by changes in the price of gold from the price ranges being experienced in the early 1980's. An unpublished South African Minerals Bureau estimate of total life-of-mine reserves for all South African gold mines is within ±15 pct of that presented herein.

Three major factors affect an assessment of Witwatersrand Basin gold reserves. They are discussed separately as follows:

Pay limit — The pay limit is the lowest grade of recoverable gold needed in a certain defined tonnage to economically recover the gold in that tonnage at gold prices prevalent at the time. Pay limits vary from mine to mine and from reef to reef and change from year to year. The pay limit is an important concept in determination of the annual "proved reserve" reported. In 1980, the "norm" for the South African gold mining operations was between 2 and 3 g/mt ore, the lowest in history, owing to the extremely high gold prices being received. In a general sense, this study involves a pay limit of 2.5 g/mt ore since no reef material below that grade was proposed for mining in the underground operations analyzed.

Gold Distribution — In Witwatersrand Basin gold deposits, the gold particles occur in hard, abrasive pebble conglomerates referred to as reefs. The reefs generally have a tabular shape, with long extensions along strike and down dip. Because of channeling, the grades of gold vary from area to area within the same reef on the same mining property and from property to property. Thus, development and borehole samplings are based on varying sampling widths, and any estimation of reserve or resource potential must adjust these sampling results to an expected or assumed mining width.

Structural factors — The gold-bearing reefs in the Witwatersrand Basin have wide variations in the degree of dip attitudes, ranging from 10° to nearly 30°. At many properties, the reefs have been subjected to local faulting, which can cause losses of 20 to 30 pct of the available tonnage.

The life-of-mine reserve estimate of this study is considered as equivalent to the demonstrated resource category and is presented in table 11 along with a comparison of the estimate for the past production values from 1885 through 1983.

As shown in table 11, the 1984 demonstrated resource for the 44 evaluated South African gold mining operations totals 5.065 billion mt. It includes 2.988 billion mt underground material on a mill feed basis and 2.077 billion mt old surface mine dumps and mill tailings dam material. The underground ore has an overall weighted-average mill feed grade of 7.7 g/mt and a recovery grade of 7.3 g/mt, while the surface reclamation material grades an extremely low 0.29 g/mt contained and 0.21 g/mt recoverable gold. Total contained gold is estimated at 758 million tr oz grading 4.7 g/mt overall. At an average recovery of 94 pct, total recoverable gold is estimated at 716 million tr oz. Of this total, 98 pct is available from underground ore and 2 pct from surface reclamation sites.

The total demonstrated resource estimate for each operation takes into consideration such factors as current capital expansions, ongoing development plans, and mining lease applications in order to estimate the total amount of gold potentially recoverable from each operation. The total estimate for the underground resource covers only those reefs under production or announced for planned production as of 1981. The estimate does not include any reef material grading less than 2.5 g/mt or reefs present on holdings under exploration lease.

A few underground operations mined reef material that graded as low as 2.5 g/mt during 1981–82; however, this low-grade underground material was supplemental mill feed for the main ore source(s), which were usually relatively high-grade material. This study estimates that underground material grading 2.5 g/mt or less cannot be produced economically at the price levels of the early 1980's.

Historically, production has come from numerous reefs in the Witwatersrand Basin. Nearly all of these productive reefs occur in what is referred to as the Witwatersrand Triad, which involves, collectively, three separate geological systems — the Dominion Reef System, the Witwatersrand System, and the Ventersdorp System. The majority of production has come from seven individual reefs or reef groups which also contain 97 pct of the total underground demonstrated resource of this study.

Table 12 lists all nine reefs or reef groups comprising this study's 1984 demonstrated resource estimate along with information on the total tonnage and grade range estimates for the reefs or reef groups, by gold mining field. All nine of these reefs are located in the upper division of the Witwatersrand System or in the lower portion of the

Table 12.—Distribution of demonstrated gold resources in South Africa, by reef or reef group and by gold mining field

Reef or reef group	Total underground demonstrated resource		Number of producers mining reef or reef group							
	Tonnage, 10^6 mt	Feed grade range, g/mt	Total	East Rand	Central Rand	West Rand	Far West Rand	Klerksdorp	OFS	Evander
Kimberly Reef	245	3.0- 7.3	11	3	2	2	0	0	0	4
Carbon Leader Reef	206	9.4-18.8	4	0	0	0	4	0	0	0
Basal Reef	611	6.2-11.4	9	0	0	0	0	0	9	0
Leader Reef	278	2.5- 3.5	7	0	0	0	0	0	7	0
Main and South Reefs	375	3.5- 7.0	8	1	1	4	2	0	0	0
Vaal Reef	391	9.0-11.0	4	0	0	0	0	4	0	0
Ventersdorp Contact Reef and Elsburg Reefs	790	3.5-14.8	15	0	0	7	4	2	2	0
"A" and "B" Reefs of Kimberly group	82	4.3- 7.8	3	0	0	0	0	0	3	0
Main Reef Leader, Black Reef, and Middle Reef of OFS	10	4.6-11.1	4	3	0	0	0	0	1	0
Total or average	2,988	2.5-18.6	NM	7	3	13	10	6	22	4

NM Not meaningful.

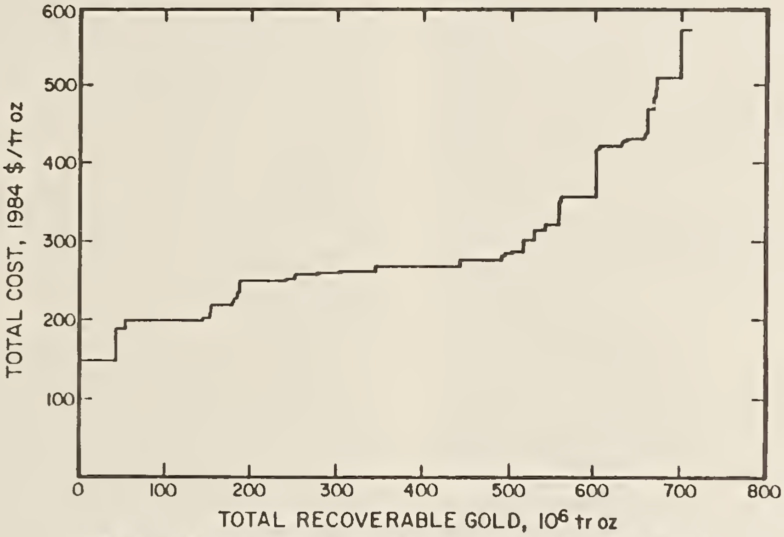

Figure 12.—Potential total South African gold available at break-even costs of production as of January 1984.

Ventersdorp System. Feed grades range from 2.5 g/mt milled to18.6 g/mt milled. The Leader Reef in the Orange Free State Goldfield has the lowest grade range, 2.5 to 3.5 g/mt; thus, it is milled along with the relatively high-grade Basal Reef materials grading 6.2 to 11.4 g/mt. The Carbon Leader Reef in the Far West Rand Goldfield, at 9.4 to 18.6 g/mt, and the Vaal Reef in the Klerksdorp Goldfield, at 9.0 to 11.0 g/mt, are the highest grade reefs. In terms of distribution among the various goldfields, the Main and South Reef groups, the Kimberly Reef, and the VCR-Elsburg Reef group are the most common, all being present in four of the seven goldfields.

TOTAL AVAILABLE GOLD FROM PRODUCING SOUTH AFRICAN MINES

The 44 largest primary gold producing operations, accounting for 97 pct of total 1983 production, were evaluated. These operations are listed in table 1.

Total refined gold potentially recoverable from all operations is estimated at 716 million tr oz: 702 million tr oz from underground mines and 14 million tr oz from surface operations. This represents approximately 16 yr of total world production or 32 yr of South African production at 1984 levels.

Figure 12 shows the total amount of refined gold cumulatively available at increasing cost levels from all 44 evaluated operations.

In January 1984 dollars, long-term break-even production costs (as defined in the appendix) range from $148/tr oz to $573/tr oz. Seventy-three percent of potentially available refined gold is recoverable at a cost level of $300/tr oz or less, 85 pct is recoverable at $400/tr oz or less, and more than 94 pct is recoverable at $500/tr oz or less. The price of gold averaged $425/tr oz in 1983, which indicates that the great majority of South African gold resources are economic. This average 1983 price is lower than the $459 average price recorded in 1981 and markedly lower than the $612 average recorded for 1980, but it still represents a 334-pct increase over average 1973 prices. These high prices are responsible for the ambitious development and expansion plans that were announced in 1980–82 in South Africa and which have been incorporated into this analysis.

Table 13 shows the total amount of refined gold cumulatively available at increasing cost levels from the 38 underground mines. The weighted average long-term cost of refined gold production for all 38 underground mines is estimated at $285/tr oz. The lowest cost underground mine is estimated at $148/tr oz. This weighted average reflects the influence of a number of exceptionally large and profitable mines. Seven of these 38 underground mines, for example, are estimated to each contain in excess of 40 million tr oz recoverable gold, and an additional 5 underground mines are estimated to each contain in excess of 20 million tr oz recoverable gold. For the six low-grade

Table 13—Total gold potentially available at increasing cost or price levels from 38 underground operations in South Africa

Gold cost or price level, per troy ounce	Break-even DCFROR		10-pct DCFROR	
	Available gold, 10^6 tr oz (cumulative)	Number of mines (cumulative)	Available gold, 10^6 tr oz (cumulative)	Number of mines (cumulative)
$200	143.2	3	51.7	2
$300	515.8	21	450.0	17
$400	600.2	28	600.2	28
$500	664.1	36	661.4	34
Over $500	701.7	38	701.7	38

sand and slimes dump reprocessing operations, the weighted average long-term break-even cost is estimated at $335/tr oz refined gold.

The overriding importance of a small number of large underground South African mines is demonstrated by the data of table 14. The 10 largest mines in terms of total recoverable gold account for 481 million tr oz. This is 67 pct of total South African gold and 59 pct of evaluated total MEC recoverable gold. The long-term break-even unit cost of these 10 mines ranges from $148/tr oz to $509/tr oz with a weighted average of $273.

Table 14.—Ten largest South African operations in terms of total recoverable gold[1]

Operation name	Ownership
Dreifontein Consolidated	Gold Fields.
Vaal Reefs	Anglo American.
Western Deep Levels	Do.
Free State Geduld	Do.
Kloof	Gold Fields.
Western Holdings Complex	Consortium of 4 owners.
Randfontein Estates	Johannesburg Consolidated.
East Rand Proprietary	Barlow Rand.
President Steyn-Video	Anglo American.
Harmony	Barlow Rand.

[1]Total recoverable gold = 481 million tr oz:
Percent of South African gold = 67.
Percent of market economy country gold = 59.
Long-run total unit cost:
Range = $148 to $509.
Weighted average = $273.

As shown in table 15, 9 of these underground operations are also listed among the 10 largest average annual producers on a life-of-mine basis. The 10 operations in table 15 account for approximately 55 pct of expected average annual South African production during the 1984–90 period and for approximately 45 pct of expected average annual MEC production from the 111 evaluated operations during this same period. The ownership of this large annual productive capacity and total recoverable gold is concentrated in five of the large mining houses in South Africa. Given that these mining houses own other mines both inside and outside South Africa, they represent a large percentage of world gold ownership and supply as well.

In table 16, the 10 lowest cost underground producers are listed according to this study's estimate of long-run total break-even unit cost. Four of the 10 operations contained in this listing are also among the 10 largest annual life-of-mine producers. All 10 of these operations have long-term break-even unit costs below $250/tr oz.

Given South Africa's current dominant production position and its very large quantity of total and annual gold available at relatively low break-even cost levels, it would appear that its industry currently establishes the minimum floor price of newly mined gold. This means only that free market gold prices could not remain below this average South African cost level for long without causing either major contractions in world supply of newly mined gold or large South African Government assistance payments to keep that nation's gold mines operating. The two mines with long-run unit costs estimated to be above $500/tr oz (table 13) have long received state assistance. It is important to stress, however, that the gold mines of South Africa are not state owned and are profit motivated. In this regard, the analyses at the 10-pct profitability level determined long-run total costs ranging from $157/tr oz to $618/tr oz, with a weighted average for all underground mines of $302/tr oz.

Table 15.—Ten largest South African operations in terms of average annual life-of-mine production[1]

Operation Name	Ownership
Dreifontein Consolidated	Gold Fields.
Vaal Reefs	Anglo American.
Western Deep Levels	Do.
Randfontein Estates	Johannesburg.
Free State Geduld	Anglo American.
Western Holdings Complex	Consortium of 4 owners.
Harmony	Barlow Rand.
Kloof	Gold Fields.
Buffelsfontein[2]	Gencor.
President Steyn-Video	Anglo American.

[1]Total average annual output = 12.8 million tr oz.
Percent of average annual South African production (1984–90) = 55.
Percent of average annual production from 111 operations (1984–90) = 45.
[2]Only operation not on 10 largest recoverable gold list.

Table 16.—Ten lowest cost producers in terms of long-run total break-even production cost

Operation name	Cost level per troy ounce
Kloof[1]	Less than $210.
Kinross	Do.
Dreifontein Consolidated[1]	Do.
Winkelhaak	Do.
Blyvooruitzicht	Do.
Buffelsfontein[1]	Less than $250
Unisel	Do.
E. T. Consolidated	Do.
Western Deep Levels[1]	Do.
Doornfontein	Do.

[1]Among the 10 largest average annual life-of-mine producers.

Economic Effect of Byproduct Production

Many of the operations produce other mineral products in association with gold. The most notable is uranium; silver, pyrite concentrates, and sulfuric acid are also produced. Silver production for all operations is a byproduct of primary gold production. Revenue generated from silver production is insignificant, generally less than 1 or 2 pct of the total. The total amount of silver recoverable along with the gold from 42 operations is estimated at approximately 67 million tr oz. Eighteen operations contain less than 500,000 tr oz silver, and 18 contain over 1 million. Only eight operations are estimated to have average annual production levels exceeding 100,000 tr oz silver contained in total annual dore bullion production.

Most South African uranium production is a byproduct of gold production. In contrast to the situation for gold, data relating to contract prices and production are difficult to obtain. Of the underground operations that produce uranium, six produce enough (or contain enough) that the overall economics of the operation are affected by potential uranium revenues. In only two cases, however, is it felt that uranium revenues are essential to the economic competitiveness of the operation. During 1984, four operations announced their intention to cease byproduct uranium production. One of these operations is converting its uranium plant to a gold treatment plant, and at least one other operation is considering doing the same.

A portion of total uranium production is derived from primary uranium mines. One of these has decided to close down indefinitely, and two have converted to become primary gold producers (*8*, pp. 296–297). The current uranium market situation is quite poor, as is reflected in the conversions occurring in 1983 and 1984. It can be expected that a certain level of uranium production will be maintained owing to political consideration of the South African Government.

Capital and Operating Costs

Underground gold mining in South Africa is somewhat anomalous in that it is both highly labor intensive and requires high levels of capital investments and reinvestments. Data on capital and operating costs as estimated in this study are included in table 17. Total capital investments and reinvestments over the estimated remaining mine lives range from $15 million to $3.8 billion per operation.

Table 17.—Economic summary data for 38 underground gold mines in South Africa

	Range	Total or weighted average
Operational data:		
Average annual output ......10^3 tr oz.......	30–2,100	21,000
Total recoverable gold[1] ......10^6 tr oz.......	670–91,450	702
Producing years from January 1984..............	6–63	NAp
Capital and operating cost data:		
Total capital investment[2] ...10^6dollars ...	$15–$3,835	$33,150
Annual capital reinvestment ......do	$1–$98	NAp
Capital cost per troy ounce	$7–$95	$52
Operating cost per troy ounce[3]	$123–$488	$247
Total operating plus capital cost per troy ounce	$145–$599	$299
Long-run total cost per troy ounce:		
Break-even (0-pct DCFROR)	$148–$573	[4]$285
10-pct DCFROR	$157–$618	$302

NAp Not applicable.
[1]Refined gold estimated to be recoverable as of Jan. 1984.
[2]Unrecovered capital investment in mine and mill plant and equipment, infrastructure, and development remaining as of Jan. 1984 and reinvestments through life of operation.
[3]Mining plus milling cost per troy ounce of refined gold.
[4]Less than total operating plus capital cost owing to influence of byproduct credits for uranium.

Thirteen operations will require between $500 million and $1.0 billion in total capital investments, eight will require in excess of $1.0 billion, and four will require in excess of $3.0 billion of investments over their estimated remaining mine lives.

On an annual life-of-mine basis, total capital reinvestments are estimated to range between $1.0 million and $98.0 million with 50 pct of the operations in the $10.0 to $50.0 million range. South African tax law allows for the expensing (1-yr writeoff) of capital expenditures in the year incurred. Capital costs per ounce of recoverable gold are remarkably similar for most operations, which indicates that, to a certain degree, capital costs reflect adjustments by the operations to the grade of ore and mining conditions that are encountered. Thirty of the operations have capital costs per ounce of recovered gold ranging between $30 and $60.

Operating costs per ounce of recoverable gold show a wide range over all operations ($123 to $488), but at least 50 pct of all operations have estimated costs between $150/tr oz and $250/tr oz.

The single most important component of operating cost is labor, which accounts for an average of approximately 48 pct of basic mining costs and 42 pct of basic milling costs. Another factor input of importance is the capital cost of mining and milling equipment and replacement parts. Figure 13 plots index data on the rate of increase since 1970 in both of these two major components of South African gold production costs, i.e., basic wage costs (with no allowance for productivity changes, fringe benefits, etc.) and mining and milling equipment costs (*9*, pp. F1–F2). Both general cost categories have steadily increased since the early 1970's, with wage costs increasing at a faster rate than equipment costs. This is attributable to both rising gold revenues and rising expectations of black mine workers. Changes in labor relations have recently culminated in the legalization of black mine workers' unions. Labor wage costs in South Africa have increased at an average rate of 17 pct annually since 1978. It was in this year that labor wage costs began to rise faster than the cost of mining and milling equipment, which has risen at an average annual rate of 12.5 pct since 1978.

Also shown in figure 13 are the U.S. dollar-based equivalents of these two index series. Since 1980, the gap between the cost of labor and equipment in rands and the cost in dollars has widened significantly owing to the devaluation of the rand. This devaluation has offset both rising rand-based production costs and declining U.S. dollar-based gold prices.

The operating cost data shown in table 17 reflect a constant 1984 dollar analysis. It is interesting though to look at possible future trends in production costs based on the assumption of continued wage cost increases at South African gold mining operations. Toward that end, an analysis was performed that addressed this issue in the following manner. First, the trends in the cost of major factors of production since 1978 were ascertained. Second, this information was used to escalate mine and mill operating costs for a 10-yr period, 1985–94. These escalated costs were then held constant at their 1994 values for the duration of the mines' productive life and were employed in reestimating long-run total break-even unit costs of production. Lastly, these determined unit costs under the escalation scenario were compared to the constant 1984 base case costs derived earlier.

Since 1978, combined rand-based mine and mill operating costs have increased at an average annual rate of 16 pct. This analysis assumed that this rate will continue during 1985–94 and that the rand will continue to devalue at an assumed average rate of 8 pct/yr, thus offsetting only one-half of the rand-based cost increase. This results in an annual 8-pct U.S. dollar-based cost increase for all operations during 1985–94.

The results of this analysis are given in table 18. As shown in the escalating cost case, 18 operations (containing 53 pct of available gold) have total production cost estimates below $500/tr oz, as compared to 36 operations (containing 95 pct of available gold) under the base case

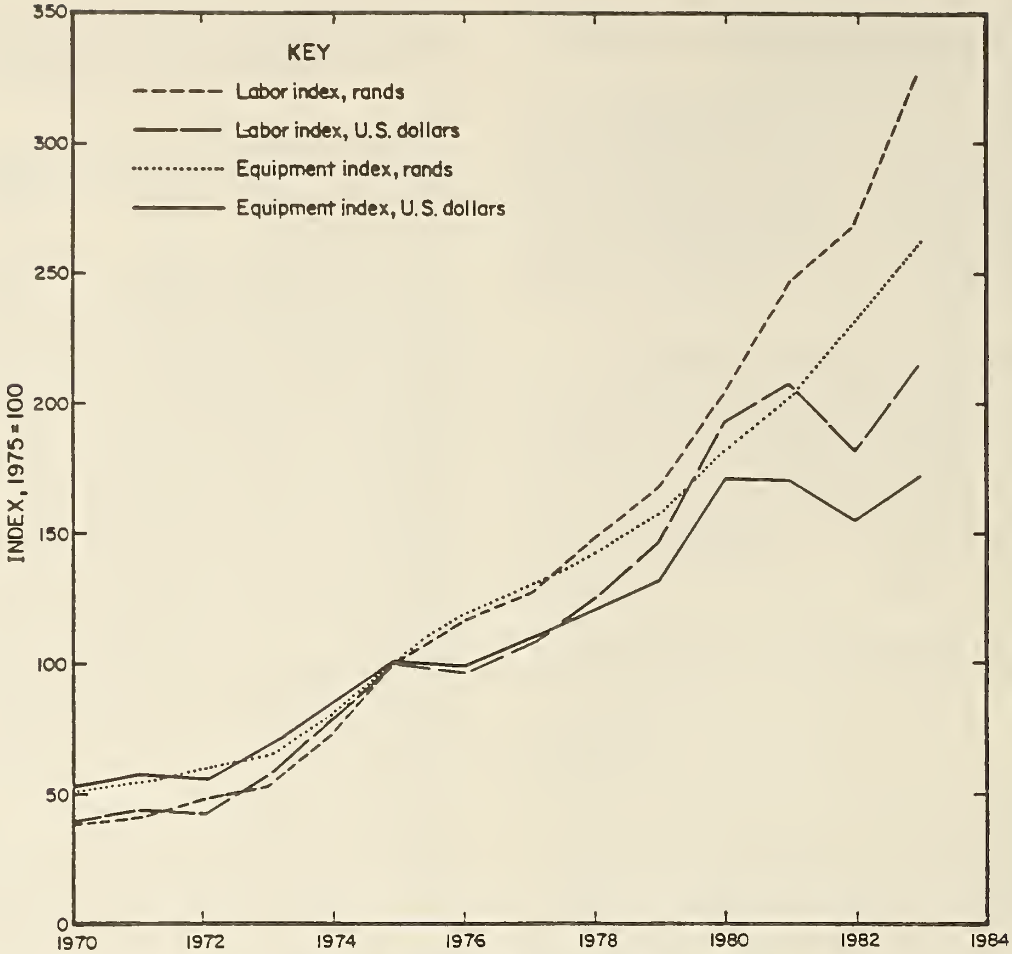

Figure 13.—Rate of increase in labor and equipment costs in rand and dollar terms, 1970–83.

Table 18.—Total South African gold potentially available at increasing cost or price levels: base case versus 8–pct–escalation case

Gold cost or price level, per troy ounce	Available gold at break-even DCFROR, 10^6 tr oz (cumulative)		Number of operations (cumulative)	
	Base case	Escalated case	Base case	Escalated case
$200	143.2	0	3	0
$300	515.8	54.3	21	3
$400	600.2	70.5	28	7
$500	664.1	368.9	36	18
Over $500	701.7	701.7	38	38

scenario. Thus, without devaluation of the currency to offset wage cost increases, the economics of gold production in South Africa could be severely affected. This analysis, however, actually serves to underscore the long-term competitiveness of the South African mines for four reasons. First, it is not at all implausible to assume that dollar-based production costs in other major producing countries will also arise at an 8-pct average rate. Second, it is also not implausible to assume that the price of gold during the next 10 yr will increase at an average rate of 8 pct/yr in 1984 U.S. dollar terms. Third, even if labor wage costs more than double, as assumed in this analysis, and U.S. labor wage costs remain constant, average South African wage costs would still be only about one-third of the U.S. level. Fourth, gold is not expected to become a commodity where producers compete for a tight or dwindling market plagued by oversupply or lack of demand because production costs and mine production do not influence market price. The gold price is demand driven, and it is fully expected that South African production will continue to adjust to market prices and remain the most significant supplier for the rest of this century.

Effect of Exchange Rate Variation Upon Industry Profitability

The profitability of South African mines has been significantly affected recently by variations in the value of the rand relative to the U.S. dollar. Since September 1983, South African mines have been paid directly in U.S. dollars for their gold production. This has had the effect of transferring foreign exchange gains to the mines, which has helped to offset rising rand-based production costs. For example, during 1981–83 rand-based production costs increased between 28 and 30 pct. But during this same time period the rand-dollar exchange rate depreciated some 27 pct. The result has been that dollar-based gold production costs in South Africa have increased only 1 to 3 pct from 1981 through 1983.

This foreign exchange gain has also helped to offset declining dollar-based gold prices. Where transactions involve a dollar-rand exchange rate (the "dollar price of the rand") that has declined more than the dollar price of gold, the rand price of gold has actually increased. This helps to maintain profitability for the majority of South African mines. Figure 14 presents data on total gold revenues expressed in rands and U.S. dollars. Of particular importance is the period 1980–83.

During 1980, the average annual price of gold reached an historic high of $612/tr oz. South African gold production was 21.7 million tr oz., which generated total industry revenues of $13.3 billion. At the average annual exchange rate, this was the equivalent of 10.3 billion rands (R). From 1980 to 1983, the average annual dollar price of gold fell 30 pct, and South African gold production, at 21.8 million oz, was essentially the same as in 1980. Thus, dollar-based revenues for 1983 also fell 30 pct to $9.3 billion. Revenues in rands, however, were unchanged at R10.3 billion because the dollar-rand exchange rate had also declined by an equivalent 30 pct. Thus, the devaluation of the rand offset the falling dollar price of gold and helped maintain industry profitability. South African gold production remained more or less constant from 1980 to 1983 because the price of gold in rands, and hence total rand revenues, remained more or less constant.

Not all of the foreign exchange gain observed during 1983 was transferred to the mines themselves, since payment in dollars did not become official until later in the year. The impetus for such a payment change is evident from figure 14, where it can be seen that in 1981 the dollar curve dropped below the rand curve due to the rand falling below parity (R1 = $1) with the dollar. The gap between the dollar curve and the rand curve is the average foreign exchange gain accruing due to the rand devaluation. The driving force for this devaluation was the declining dollar-based gold price itself as well as a positive inflation differential between South Africa and the United States. With rand-based costs rising 14 to 16 pct/yr and dollar-based revenues falling, a change to enhance profitability became an economic imperative.

Preliminary data for the first 6 months of 1984 show that this trend has continued. The dollar price of gold had fallen to a 6-month average of $381/tr oz, a decline of approximately 9 pct relative to the average 1983 price. The dollar-rand exchange rate during this same period had fallen by approximately 11 pct, thus causing rand-based gold prices to rise slightly (R4/tr oz to R5/tr oz). Thus, declining dollar revenues were again being offset by rising rand revenues, and profitability was being maintained.

The most recent data available on exchange rates and dollar gold prices indicate that the rand devaluation has continued at an increasing rate. The dollar price of gold has also continued to decline. If and when the price of gold begins another strong upward spiral, it is possible that the devaluation of the rand will be checked, and an appreciation would be in order given a large enough increase in the dollar price of gold. By definition, a rising dollar gold price means that the value of the dollar is declining relative to gold, but not necessarily relative to the rand.

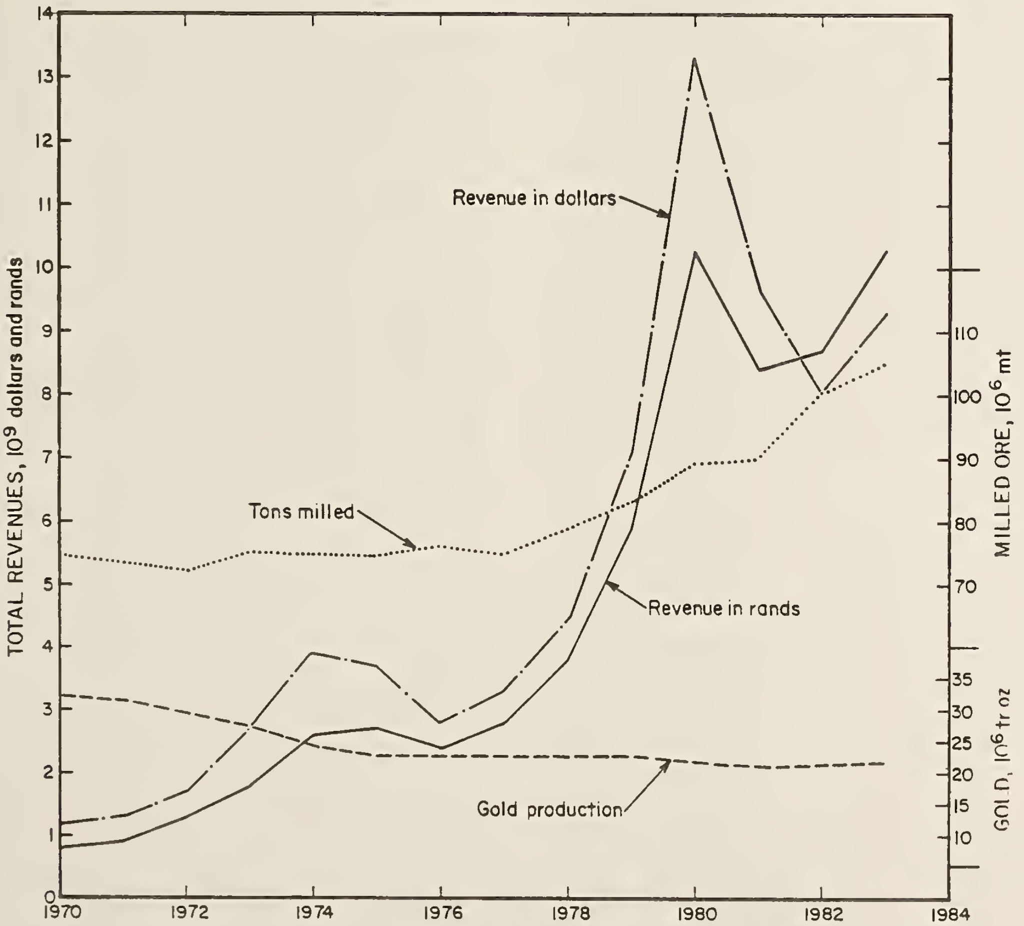

Figure 14.—Total gold revenues in rands and dollars, 1970–83.

Annual Production Potential

How long the gold resources of South Africa last will be determined by the differential between long-term production cost and market price, current production rates, expansion plans for existing mines, and the development of new mines in the future.

It appears that the South African gold industry, far from stagnating or declining, remains very optimistic about the future of gold mining in that country. For example, General Union Mining Corp. (Gencor) has recently announced the development of a new mine (not included in our analysis) in the Evander Goldfield of Eastern Transvaal. The Poplar Mine is estimated (*10*, p. 10) to contain approximately 60 million mt recoverable ore with an average recovery grade of 5 g/mt over the mine life. This equates to about 9.6 million tr oz recoverable gold. To put the size of the resource base at this one property into perspective, the Poplar Mine alone is estimated to contain more gold than the demonstrated resources of the top 12 producing gold mines in Zimbabwe, which is ranked 11th in world production. At an initial production capacity of 175,000 to 275,000 tr oz/yr, Poplar would be considered average to small in size relative to existing South African mines, yet it would be as large or larger than either of the two newest major gold mines in the United States — McLaughlin (under development) and Jerritt Canyon (producing). Poplar may begin producing by 1988.

Another new South African mine development, the Beatrix Mine, began producing in December 1983. This mine was included in our analysis. It is estimated to have approximately 40 million mt recoverable ore with a mill feed grade of 6 g/mt. Annual production is currently estimated at 350,000 to 375,000 tr oz refined gold. According to production plans for 1985, this mine alone will produce almost as much gold in that year as total projected production for the entire gold mining industry in Zimbabwe.

These two new mine developments are simply extensions of producing goldfields (Evander and Orange Free State) that in at least one case have been known about for years. In addition, expansions to capacity or maintenance of production by developing new shaft systems at presently producing mines essentially represent new mine development as well. For example, the consolidation of the East and West Driefontein operations will allow the North Driefontein area to be exploited as an addition to this merged operation rather than as a new mine. The North Driefontein area is estimated to contain approximately 27 million mt ore grading 14.3 g/mt or 12.4 million tr oz contained gold (*11*, p. 135). The merger of West and East Driefontein may allow the boundary pillars separating them to be mined. These pillars alone are estimated to contain approximately 900,000 tr oz gold.

Another example of South Africa's potential for expansion is Randfontein Estates, one of the oldest mines in the country, which began exploitation of the Cooke section (6 to 8 miles south of the old mine) in 1973 (*12*). The Cooke section, although part of the old Randfontein Estates operation, still represents a new mine development. In addition, sinking and development of the new No. 3 shaft in the Cooke section is expected to be completed by 1985. This new shaft will increase output significantly and is also essentially a new mine development.

The preceding examples show that significant development activity continues in the gold mining industry of South Africa. They also underscore the difficulty of predicting future production and the life of gold-bearing resources based upon a static analysis. The typical assumptions that are usually employed for predicting future gold production in South Africa follow:

1. Output from each mine will remain at current full-capacity levels (which may or may not include expansions underway).
2. No new discoveries will be made.
3. Some new mines in already proven areas will be developed.

The result of this type of static analysis is invariably the prediction of rapidly declining total annual production as the demonstrated resources of existing mines are exhausted and not replenished. This results in South Africa experiencing a decreasing percentage share of the world new gold market and the implication of nearly complete overall resource exhaustion. These two very recent new mine examples (Beatrix and Poplar), along with numerous expansions of existing operations, show the potential for error, especially underestimation, that exists under this type of static scenario. In fact, of the 44 evaluated operations, 6 underground and 6 surface waste reprocessing operations were not in production in 1975.

With the above discussion as an important caveat, the reader is referred to figure 15, which presents estimates of potential annual gold production available at three different break-even cost-price levels ($300, $400, and $500) for

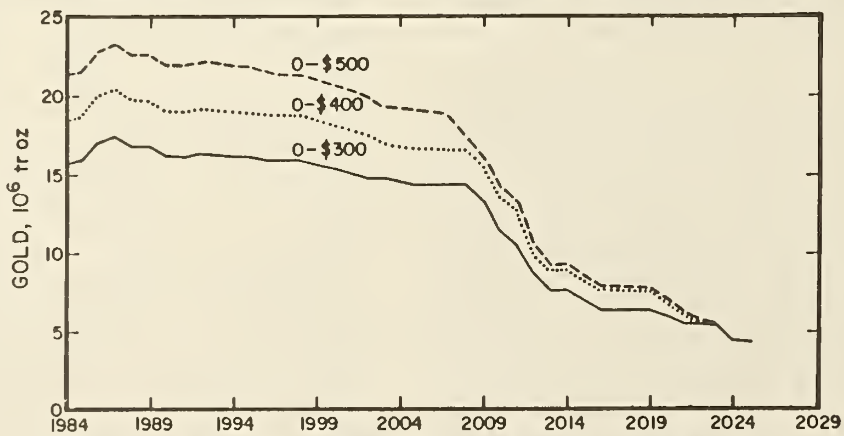

Figure 15.—Potential annual South African gold available at various break-even production cost levels, as of January 1984.

Table 19.—Estimates of potential annual South African production capabilities, thousand troy ounces

Year	Number of mines in operation[1]	Bureau of Mines projections	Gold Institute projections(*2*)	Chamber of Mines Projections (*13*, p. 333)
1984	44	21,788	22,184	NA
1985	43	22,088	22,505	NA
1988	43	23,395	22,505	NA
1987	43	23,816	NA	NA
1990	40	22,534	NA	[2]23,148
1995	39	22,382	NA	NA
2000	36	21,303	NA	[3]21,862 [4]20,094 [2]16,325
2005	30	19,531	NA	[3]18,004 [4]15,432
2010	24	14,905	NA	NA
2020	16	7,773	NA	NA
2030	6	511	NA	NA
2040	4	484	NA	NA

Not available. [1]According to Bureau of Mines. [2]Static analysis. [3]Assuming a 10-mt/yr growth rate. [4]Assuming a 5-mt/yr growth rate.

Table 20.—Mine operating cost estimates for underground gold mines on the Witwatersrand, South Africa

	Low-cost mines	Medium-cost mines	High-cost mines	Total, range, or weighted average
Number of operations	10	15	10	35
Mill feed, g/mt:				
Range	3.5–7.3	3.5–10.0	4.6–16.1	3.5–16.1
Weighted average[1]	5.2	7.5	9.4	7.4
Mine operating cost range (per metric ton ore):				
Range	$24.42–$34.46	$35.19–$44.71	$46.82–$56.77	$24.42–$56.77
Weighted average	$30.28	$40.40	$49.03	$40.00
Average mine operating cost (per troy ounce of recoverable gold)[2]	$190.65	$176.24	$170.77	$176.99
Labor cost:				
Average	$17.74	$16.87	$24.32	$19.25
Percent of total mine operating cost	49	47	50	48

[1]Based on capacities circa 1981–82.
[2]Average mining cost applied to weighted-average mill feed grade and utilizing a 95-pct mill recovery factor.

1984–2025. These estimates (not including the Poplar Mine) show South African production (assuming full capacity utilization) peaking in 1987 and gradually declining through the turn of the century with significant declines thereafter. Table 19 presents additional supporting data for figure 15, including the number of mines estimated to be in operation in selected years and future production estimates by the Gold Institute (*2*) and the South African Chamber of Mines (*13*, p. 333). The estimates are very similar over the 1984–90 period. After 1990, they differ only in assumptions concerning new discoveries. (See footnotes of table 19.) In this analysis, it is expected that by the year 2000 eight currently producing underground mines will have ceased production, yet total annual production in 2000 could still approximate 21.3 million tr oz, essentially the same as in 1984, if the expansions announced or initiated are realized. Average mine life of the underground mines is approximately 30 yr, indicating a high level of production being maintained into the early 21st century. As analyzed in this study, individual mine annual output shows wide variation, with nine underground mines capable of producing more than of 1.0 million tr oz/yr of refined gold. These estimates include several large expansion or consolidation projects spurred by the rapid escalation in gold prices.

The rapid escalation of the gold price has also caused increased interest in the reprocessing of surface waste. This study evaluated only those operations treating existing low-grade sand and slimes dump material grading from 0.3 to 1.0 g/mt gold. The amount of gold estimated to be recoverable from all six evaluated reprocessing operations as of January 1984 is approximately 14 million tr oz, which represents only 2.0 pct of the total amount of recoverable gold. In only one of the six cases (Joint Metallurgical Scheme in the Orange Free State) did the study evaluate the reprocessing of slimes material being produced from current milling operations. This analysis did not address the reprocessing of tailings that will be produced by the treatment of the 3.0 billion mt of recoverable underground ore estimated to be present as of 1984; consequently there could still remain approximately 10 million tr oz of additional gold to be recovered from this source.

South African mines are required by law to mine to the average value of their reserves. This means that as prices rise, lower grade material is mined and refined gold output either declines or remains more or less constant. Rising prices thus serve to lengthen the life of the mines currently producing and increase the incentive to further explore, expand, and develop the industry. The South African gold industry is not expected to decline to a point of relative insignificance for at least 30 yr, even assuming no expansion of the resource base; however, it is certain that the next 100 yr or so will see a very significant decline of this industry, barring major new discoveries within South Africa.

Other estimates of the long-term gold production potential of South Africa differ from those made in this report. One source predicts that by 1992 the Soviet Union will surpass South Africa in yearly production, and that by 2000 yearly South African output will total only 11.5 million tr oz, a decline of almost 50 pct (*14*). The data of this paper (and those of the South African Chamber of Mines) argue that there is a very low probability of such a large and rapid decline, assuming that market forces are the only factors involved. As shown in table 20, the evaluation presented in this study does not show a rapid decline occurring until the first decade of the next century. Furthermore, even with an assumed 50-pct reduction in yearly output to 11.5 million tr oz, South Africa would still rank at least second in world production, unless production in either Canada, China, Brazil, or the United States increased to 5 to 8 times the current level. The probability of such increases being achieved and sustained is low.

The period beyond the year 2010, which in figure 15 shows significant declines in annual gold production,

Table 21.—Technical and operational data, within rankings as to mining cost levels, South African underground gold mines[1]

	Low-cost mines	Medium-cost mines	High-cost mines
Number of operations[2]	10	15	10
Average age of operations ... yr	28	33	34
Maximum working depths 1982–1984, m:			
Range	850–1,900	1,300–2,900	1,000–3,700
Average	1,355	2,237	2,415
Estimated final maximum working depth, m:			
Range	1,000–2,300	2,200–4,000	1,000–4,200
Average	1,590	2,789	2,878
Number of mines requiring refrigeration as of 1981	4	14	9
1981 mining productivities, tons per worker-year:			
Range	225–360	168–360	135–183
Average	297	237	162
1981 stoping widths, m:			
Range	0.90–1.64	0.90–2.06	0.98–1.65
Average	1.39	1.48	1.29
Annual operation capacity, 10^3 mt/yr:			
Range	240–7,700	1,100–7,600	270–3,400
Average	2,030	3,630	2,100
Number of production shaft systems:			
Total	22	54	33
Average per operation	2.2	3.6	3.3
Average ore capacity of shaft systems ... 10^3 mt/yr	920	1,000	640
Total ore capacity, 1981–82 ... 10^3 mt/yr	20,300	55,000	21,000

[1]Cost rankings based on mine operating cost in 1984 dollars per metric ton.
Low-cost, $25.00–$35.00; medium-cost, $35.01–$45.00; high-cost, $45.01 and above.

[2]Total of 35 rather than 38. East Driefontein and West Driefontein mines were treated as separate mines in the technical and operational data analyses; 2 operations were not included because of small remaining resources.

reflects the basic fact that any static analysis that assumes that no new discoveries will be made will always show resource exhaustion. It is not feasible here to address the question of the potential for future gold discoveries in South Africa beyond the areas and reefs analyzed in this study. It is feasible, however, to address the question of whether or not the other MEC's could increase their production enough to compensate for the decline in output resulting from the depletion of the current demonstrated resources of these 44 evaluated operations.

Ability of Other Market Economy Countries to Compensate for the Expected Decline in South African Production

The United States is currently ranked fourth in world production. In 1983, the United States produced 1.957 million tr oz gold, an increase of 42 pct over 1981 output, significantly reversing a decade-long decline. The increase came in response to tremendous exploration and development activity underway since 1974, when the gold price began to increase rapidly. Canada is currently ranked third in world production. In 1983, it produced 2.274 million tr oz gold, an increase of over 36 pct relative to 1981. By comparison, South African production from 1983 is estimated to have increased by only 3.6 pct over that of 1981, yet this small percentage increase represents 762,000 tr oz of additional gold production. This points to the fact that relatively small percentage changes in South African output are quantitatively as important as even very large percentage changes in the outputs of other major producing countries.

An example of a world-class primary gold mine that was recently brought into production is the El Indio Mine in Chile. El Indio has the potential to produce about 2.7 million tr oz from the current demonstrated resource estimate. Initial annual production is estimated at 167,000 tr oz. This size is similar to other world-class mines, such as McLaughlin or Jerritt Canyon in the United States, that are currently under development or in an early stage of production. To compensate for a projected annual decline in South African production of 1.3 million tr oz/yr between 1987 and 1990 would require the development of at least seven mines on the scale of El Indio. To replace a projected reduction in annual output of 7.6 million tr oz/yr between 1990 and 2010 (assuming no new South African discoveries) would require the development of at least 45 mines on the scale of El Indio.

A similar example can be presented using the Golden Giant Mine in the Hemlo District of Ontario, Canada. This district is the largest gold mining development in Canada in several decades and is one of the most significant ongoing developments today in the world gold industry. The Golden Giant Mine is scheduled to reach full-capacity production in 1987 at 291,000 tr oz/yr. But compensating for the 7.6-million-tr-oz decline outlined above would require the development of at least 26 new mines on the scale of the Golden Giant during the next 25 yr, while still maintaining current high levels of annual output in the other major producing nations.

The obvious implication is that other MEC's probably cannot replace gold production on a scale as large as that of South Africa, which implies declining world annual production. In terms of geologic probability, the chance of discovering another Witwatersrand-type basin, which is the largest gold producing area in South Africa, is considered to be very low.

It is expected that the significant increases in annual gold production experienced since 1980 in the United States, Canada, Australia, and Brazil (which are all major MEC producers) will continue throughout the 1980's in response to rising gold prices and continuing exploration and development activity. This will compensate for some, but clearly not all, of the decline in South African production, even accepting the relatively moderate declines outlined in this paper.

GOLD MINING IN SOUTH AFRICA

Many of the issues concerning the gold industry of South Africa are best examined from a mining engineering perspective. The following sections discuss in detail the major factors involved with the mining and processing of gold ore in South African mines. Discussion of gold mining in South Africa falls into two major categories: underground mining of primary ore, and surface reclamation of low-grade waste dumps and sand-slime tailings from prior milling. Each will be discussed separately.

Underground Mining

As already noted, 38 of the 44 operations analyzed in this study are mining primary gold ores with underground mining methods. All but 1 of the 38 produce a majority of mill feed from underground mining, and all but 2 of the 38 were producing throughout 1983. The 36 operations that produced during all of 1983 accounted for 90 to 100 million mt ore feed during that year. The other two operations began production in late 1983 or early 1984. When in full production, these new producers will add about 2.6 million mt annual ore feed from underground sources.

Of the 38 underground mines, 36 produce from Witwatersrand Basin paleoplacer gold deposits, and 2 produce from lode gold deposits in the Archean "greenstone" gold district of the Eastern Transvaal.

It is not feasible to address all of the various facets of the underground mining practices at the 38 evaluated operations. However, five aspects make the Witwatersrand Basin gold mining operations unique in comparison with other gold mining operations around the world. These unique aspects, which are important to an understanding of the availability of gold from Witwatersrand Basin deposits, follow:

1. Large-tonnage, multishaft operations.
2. Highly labor intensive, yet highly mechanized operations.
3. Mining to great vertical depths.
4. Very high capital cost requirements.
5. Technological research and constraints.

Witwatersrand Basin gold mining operations are located in an area of flat topography. The size of mining lease holdings ranges from 450 hectares (ha) to 15,750 ha, and average 5,500 ha. In total, the 36 Witwatersrand Basin properties comprise approximately 200,000 ha of mining leases. Large mining lease areas are necessary because of the thinness of the ore bodies being mined. Stoping widths (ore body thicknesses) range from 0.9 to 2.3 m with an average of slightly over 1.4 m. Thus, with the 36 mines processing a combined 95 million mt ore annually, the gold mining operations need a large area for the disposal of the tailings and the development of new ore zones. Only with favorable topographic conditions, such as occur in the Witwatersrand Basin, could such a large level of sustained production be accommodated.

As analyzed in this study, the 36 Witwatersrand Basin underground mining operations have hoisting capacities ranging from 750 to 27,000 mt/d ore and up to 14,500 mt/d waste (225,000 to 8.1 million mt/yr ore hoisted and up to 4.3 million mt/yr waste hoisted). The typical mining operation on the Witwatersrand will average about 8,300 mt/d ore and 2,200 mt/d waste (2.5 million mt/yr ore and 660,000 mt/yr waste). Of the 36 operations 29 are producing from more than 1 shaft system,[7] ranging from 2 to as many as 9 separate shaft systems at a single operation.

To extract 95 million mt ore and 25 to 30 million mt waste per year at these 36 operations requires approximately 480,000 employees for all activities including mining, milling, surface facilities, and administration. This represents productivities of only about 200 mt ore milled per worker-year, or about 0.66 mt ore per worker-shift. Detailed breakdowns of the proportion of workers employed in underground activities and those involved in surface activities are not published for all of the operations involved. Where published, it appears that about 25 to 30 pct of total employees work at surface activities, including transportation, milling, and plant activities, while 70 to 75 pct work underground. Underground mining of Witwatersrand gold ores is labor intensive for two major reasons. First, the working areas are low-backed, ranging from around 1 to 3 m in height, and extend over large horizontal and vertical distances. Thus, a typical mine will require that 10,000 m of mining face be available for stoping at any one time. Second, there are at least two or three transfers of ore from the point of extraction in the stope to delivery to the rail cars in the main haulage levels. For a more detailed description of the mining methods at Witwatersrand gold mines, the reader is referred to reference 15.

Two major constraining factors are constantly being addressed in terms of technologic research by the South African Chamber of Mines: (1) labor productivity and (2) heat, humidity, rock pressure, high rock-stress patterns, seismic events, rock bursts, and ventilation and refrigeration problems caused by the great depths of mining and the lateral extent of the workings. A discussion of all of these problems and how they are being addressed is beyond the scope of this paper. Rather, this section focuses on how this study addressed these constraining factors from a resource and cost point of view.

Tables 20 and 21 present estimated costs and technical and operational data for 35 (see footnote 2 of table 21) of the major underground operations producing in the Witwatersrand Basin in the early 1980's. The operations are categorized into three levels of mining cost on a per ton of ore milled basis: (1) low cost, or \$25 to \$35, (2) medium cost, or \$35.01 to \$45, and (3) high cost, greater than \$45. Ten of the 35 operations fall into the low-cost range with an average cost of \$30.28/mt ore. Fifteen are in the medium-cost range with an average cost of \$40.40/mt ore. Ten operations fall into the high-cost range with an average cost of \$49.03/mt ore. During 1981–82, the 10 low-cost operations accounted for about 20.3 million mt underground ore feed. The 15 medium-cost mines fed about 55 million mt underground ore to their mills, and the high-cost mines sent about 21 million mt ore to their mills. Thus, about 79 pct of total ore capacity in the early 1980's was in the medium- to high-cost range. The weighted-average mining cost for all mines is estimated to be \$40/mt ore.

Labor costs constitute the largest percentage of total mine operating cost. As estimated in this study, labor costs account for 49 pct of total mine operating cost for mines in the low-cost range, 47 pct for mines in the medium-cost range, and 50 pct for mines in the high-cost range. This aspect is very important since approximately 90 pct of the labor force are black workers who were being paid the equivalent of between \$3,000 and \$3,500 per year, circa 1981. On a weighted basis (white plus black employees combined), each mine employee was being paid between \$4,500 and \$5,000 per year in 1981, which is about 15 to 20 pct of the pay scale of employees in the U.S. gold mining industry. If U.S. mining industry pay levels existed at the gold mines in South Africa, the weighted average mining cost of \$40/mt would increase by \$109 to around \$150/mt. This would render all evaluated South African gold resources uneconomic, given 1982–84 price levels.

The operational data for the three cost categories shown in table 20 were compiled to determine the major factors involved in the increasing cost levels experienced in Witwatersrand underground mines. Before compiling the data, it was felt that five basic operational factors would affect the mining cost level by affecting productivity. These five factors were—

[7]As used in this study of the South African gold mining industry, a "shaft system" is comprised of all appropriate shafts (ventilation and production) necessary to service a specific area of the operation's overall lease area. The number of shaft systems eventually needed to mine out an entire lease area and the number of shaft systems required at any specific point in time over the life of the operation will depend on the overall size of the lease area, the company's requirements for ore and waste hoisting capacity, mill locations, and underground haulage distance limitations.

1. The number and capacity of the various shaft systems at the operations.
2. The age of the operation.
3. The depth of mining.
4. The stoping widths.
5. The percentage of waste sorted prior to milling.

As expected, the major difference found among the three cost levels is the measure of 1981 mining productivities per ton of ore milled per worker-year. As shown in table 21, the low-cost mines had average productivities of 297 mt/yr, the medium-cost mines had average productivities of 237 mt/yr, and the high-cost mines had average productivities of 162 mt/yr. Thus, average mining labor productivity is 20.2 pct lower at the medium-cost mines and 45.5 pct lower at the high-cost mines. Further analysis of the data indicates that these lower mining productivities are primarily due to the increasing depths of mining. As shown in table 21, the average maximum working depth at the low-cost mines in 1982–84 was estimated to be 1,355 m. By comparison, the average maximum working depth at the high-cost mines in 1982–84 was 2,415 m, or 1,060 m deeper in vertical depth. This link between increasing depth and declining overall mining productivity is also shown in table 22, which compares actual operating data for one South African mine in 1960 (about 7 yr after startup) and in 1981 (28 yr after startup). During this 22-yr period, the depth of mining increased 1,000 m, and despite 22 yr of technological improvements, productivity decreased 10.7 pct in terms of tons of ore plus waste hoisted and 8.5 pct in terms of tons of ore alone.

The increasing depth of mining also increases the nonlabor costs associated with hoisting and haulage, the need for refrigeration and/or the refrigeration costs, and ventilation and compressed air needs. Depending upon the area of the Witwatersrand Basin being mined, refrigeration is usually required at a vertical depth of 1,100 to 1,300 m. As shown in table 21, only 4 of the 10 low-cost mines required refrigeration as of 1981, while 23 of the 25 medium- and high-cost mines required refrigeration. The nonlabor costs for refrigeration were estimated to range from about $1.20/mt to $1.50/mt ore to $3/mt ore at those mines with the largest refrigeration requirements.

In this study, 75 to 80 pct of the $10.12 increase in average mining cost from the low- to the medium-cost levels can be attributed to increasing depth, which in turn results in decreasing labor productivity, increasing hoisting and haulage distances, and increasing refrigeration, ventilation, and compressed air needs. In turn, the increase from the medium-cost to the high-cost level of $8.63/mt ore is heavily influenced by the drop in labor productivity, with the increase in the cost of labor representing about 63 pct of the increased cost. It is possible that the decrease in ore capacity at the average-sized shaft system (from 1 million to 640,000 mt/yr) from the medium-cost to the high-cost levels magnifies the drop in labor productivity and the consequent increase in mining labor costs.

There is a final factor involved in comparisons of the various cost levels of Witwatersrand underground gold mines. This factor is the grade of ore being milled at the various cost levels. Table 20 contains the range and weighted average gold grades of the operations comprising the three cost levels based on 1981-82 ore capacities. Also shown, for comparison, are average mine operating costs for the three cost levels, in terms of dollars per metric ton of ore milled and of dollars per ounce of recoverable gold. When the cost is compared in terms of dollars per ounce of recoverable gold, the orders of the three cost levels are reversed, with the low-cost mines becoming the high cost mines and vice versa. This exercise simply verifies the fact that most of the Witwatersrand producing gold mines adjust their operations to the grade of ore available and the mining conditions encountered. Some operations have high mining costs (on a per ton of ore basis) along with low grades, which puts them in a marginally economic position, but most of the operations have mining costs that are economic given their ore grades.

Table 22.—Comparison of mining productivity changes, 1960 and 1981, based on actual results at a South African mine

	1960	1981	Change
Average level worked	10	25	NAp
Vertical depth of average level worked . . . m	1,500	2,500	+1,000
Total employees (actual)	6,848	9,246	+2,398
Employees in mining-related activities (estimate)	6,163	8,396	+2,233
Ore and waste hoisted . . . 10^3 mt	2,057	2,497	+440
Indicated mining productivity: Ore plus waste per worker-year . mt	333.8	297.4	−36.4
Ore milled . . . 10^3 mt	1,160	1,440	+280
Indicated underground productivity: Ore milled per worker-year . . . mt	188	172	−16

NAp Not applicable.

A key element in any discussion of South African underground gold mines is the question of the depth of mining, especially as it relates to cost and resource estimations. As of 1981, the deepest areas being stoped were between 3,600 and 3,700 m (about 2.3 miles) below the surface. The average maximum depth of mining in 1981 at the 38 major underground mines analyzed in South Africa was about 2,035 m, with only 2 operations working at maximum depths of over 3,000 m. It is estimated that to extract the 2.988 billion mt demonstrated underground resource estimated in this study, the 38 operations would have to mine to an average maximum mining depth of about 2,450 m. As analyzed, five of the operations will eventually be required to mine to maximum vertical depths of 3,500 to 4,100 m, and five will have to mine to maximum vertical depths of 3,100 to 3,500 m.

As of the early 1980's, it appears that at depths between 3,500 and 4,100 m, major technological problems develop in underground mining in the Witwatersrand Basin. These technological problems and a brief summary of some of the research activities involved in addressing the problem have been discussed in reference 15. Because of the problems beginning at the 3,500-m level, it is important to understand the extent to which the analyzed demonstrated resource is composed of material at depths greater than 3,500 m. Thus, at the five operations that are proposed to mine to maximum depths of greater than 3,500 m, about 0.16 billion mt (5.4 pct) of the 2.988-billion-mt demonstrated resource is located below the 3,500-m-depth level. This tonnage of ore would contain approximately 43 million tr oz (6.1 pct) of the 702 million tr oz of total recoverable gold in the underground demonstrated resource that was evaluated. This study assumes that this 43 million tr oz will actually turn out to be recoverable, but such an assumption is open to question and much will depend upon future developments. In this regard, it should be remembered that the majority of those operations facing maximum mining depths between 3,500 and 4,100 m will not reach these depths until the middle to late 1990's.

Overall, only seven operations are expected to have the average mining depth increase by more than 1,000 m beyond the 1981–82 levels. At another eight operations, the expected increase in average depth of mining would be 500

Table 23.—South African milling methods and capacities

Mill category and methods	Number of mills or mill extensions	Mill or extension capacities, 10^3 mt		Total capacity by milling method, 10^3 mt/yr
		Range	Average	
Gold production only:				
Underground material:				
Crush-grind-cyanide vat leach, Merrill-Crowe-zinc dust precipitation	24	270 - 2,750	1,830	[1]43,900
Crush-grind-cyanide vat leach, carbon-in-pulp	6	240 - 2,000	1,280	[1]7,600
Crush-grind-gravity separation, float-roast concentrates, cyanide-leach calcines	4	65 - 165	115	[1]460
Surface material: Sand and slimes retreatment	3	600 - 1,300	900	[2]2,700
Gold and pyrite concentrate production:				
Crush-grind-cyanide vat leach, Merrill-Crowe-zinc dust precipitation, float tails for pyrite concentrate	2	1,320 - 2,250	1,800	[1]3,600
Gold and uranium production:				
Crush-grind-vat leach for gold	19	630 - 3,180	2,200	[1]41,800
Crush-grind-vat leach for uranium	19	630 - 3,250	2,400	[3]45,600
Old sand and slimes and current slimes treatment	3	6,600 - 23,400	16,400	[2]49,200
Total	80	65 - 23,400	NM	NM

NM Not meaningful.
[1]Total milling capacity for underground gold ore = 97.36 million mt/yr ore milled.
[2]Total milling capacity for gold in old and current sands and slimes = 51.9 million mt/yr milled.
[3]Total milling capacity for U_3O_8 production from underground ore = 45.8 million mt/yr milled.

to 1,000 m. For this study, all 15 operations were assumed to incur actual real decreases in labor productivity of 10 pct over the life of the operations. In addition, at all of the evaluated operations, rough estimates of increased haulage and hoisting distances and increased refrigeration, compressed air, and ventilation requirements were included in the cost estimates.

Surface Mining

Surface mining of South African gold ores involves only the reclamation of material from waste and sand dumps and slimes dams. The material is used either as partial feed to primary milling with underground ore as the primary feed source, or as the primary feed for reprocessing plants. Where a dump consists predominantly of coarse material such as sand and rock, the equipment combinations for reclamation include shovels feeding conveyor belts or, more commonly, front-end loaders with trucks. Where the reclamation material is predominantly slimes material, either bucket wheel excavators with conveyor belts or water-jet monitors feeding a slurry to pipelines are used.

The distances that the material is transported to the mill site range from 0.5 to 7 km for the non-slurry-pipeline operations. The operations using slurry pipelines for transporting slimes material require pipeline lengths of 2 to 14 km. Because the material being reclaimed is very low in terms of gold grade, the mine operating costs at operations using this material as the primary feed are very sensitive to the length of conveyance required. The estimated mine operating costs used in this study for shovel and/or conveyor operations range from $1/mt to $2.25/mt ore, while front-end loader and truck operations were estimated to have operating costs in the $2.50/mt to $3.50/mt range. The operating costs for the bucket wheel excavation and conveyor belt operations were estimated to be about $2/mt material, while slurry pipeline operating costs were estimated to range from $0.10/mt to $0.60/mt slimes reclaimed. In contrast to the underground mining costs, labor constitutes a minor portion of these operating costs, or about 20 to 30 pct of the total.

GOLD MILLING IN SOUTH AFRICA

Milling treatment practices at the 44 operations analyzed in this study can be generally categorized into 6 basic methods:

1. Crushing, grinding, agitation leaching with cyanide, Merrill-Crowe deaeration, zinc dust precipitation, smelting to dore bullion.
2. Crushing, grinding, agitation leaching with cyanide, carbon-in-pulp extraction of gold, stripping of carbon, electrowinning of gold, smelting to dore bullion.
3. Crushing, grinding, agitation leaching with cyanide, float tails from cyanide leach for pyrite concentrate production, deaeration-precipitation-smelting to dore bullion.
4. Crushing, grinding, gravity separation, flotation, roast concentrate, cyanide leaching of calcine from roasting, deaeration-precipitation-smelting to dore bullion.
5. Crushing, grinding, flotation, cyanide leach for gold, MnO_2 and H_2SO_4 leach for U_3O_8, production of sulfuric acid from flotation concentrate.
6. Treatment of sand and slimes dump material.

As shown in table 23, the 44 evaluated operations contain 80 individual mills. All of the operations involve vat leaching of gold and/or U_3O_8; as of 1984 no heap leaching was practiced at any of the major gold operations. For convenience, the milling operations in South Africa can be split into three major groups as shown in table 23. The groupings were made according to the various commodities produced as follows:

1. Those producing only gold bullion.
2. Those producing gold bullion and pyrite concentrate.
3. Those producing gold bullion and U_3O_8 (in the form of uranium hexafluoride) along with pyrite concentrates and/or sulfuric acid either for their own use or for sale to other operations.

As shown in the footnotes to table 23, the analyzed milling capacity for treatment of underground ore totals 97.36 million mt/yr, while the milling capacity at those operations that reprocess dump material for producing gold, uranium, pyrite, and sulfuric acid totals 51.9 million mt/yr feed material.

Of the 80 mills, 19 were constructed to produce uranium and 61 were constructed to produce gold. Of the 61 gold mills, only 6 are using the carbon-in-pulp method of extracting gold from the cyanide leach solution. The other 55 use the old Merrill-Crowe deaeration-clarification method along with zinc dust precipitation of the gold. Not surprisingly, all of the carbon-in-pulp mills have been constructed since 1979. As of 1984, nearly all of the planned new mills in South Africa will probably use carbon methods for gold extraction. The vast preponderance of Merrill-Crowe plants in South Africa as of 1984 is due to the fact that the vast majority of mills were constructed prior to 1980 and to the historical availability of a low-cost labor force.

The four mills that use gravity separation along with flotation and subsequent roasting of the flotation concentrate and cyanide leaching of the calcine from roasting are all part of the two evaluated operations in the Eastern Transvaal. Gold ores in the Eastern Transvaal are of a very refractory nature and contain a fair amount of free gold, the opposite of a typical Witwatersrand Basin gold ore. At these mills in the Eastern Transvaal, typically 30 to 45 pct of the gold recovered comes from gravity separation (free gold). Of the remainder, 10 to 20 pct is usually contained in the middlings from gravity separation, and 40 to 55 pct is in the flotation concentrate, both of which are then roasted and leached. Estimated milling costs for these operations ranged from \$7.01/mt to \$14.34/mt ore milled, with labor estimated to account for about 25 pct of the total milling costs. These costs also include fairly lengthy truck haulages for middlings and flotation concentrate products to the smelter. This category of milling represents only 0.5 pct of the total South African underground ore milling capacity analyzed.

The six mills treating underground ore with carbon-in-pulp gold extraction methods represent an approximate total milling capacity, as of 1984, of 7.6 million mt/yr, or only about 8 pct of total underground ore milling capacity. Estimated mill operating costs for the capacity ranges of 240,000 to 2 million mt/yr have a narrow range of \$4.98/mt to \$7.53/mt ore milled with an average of \$6.11/mt. Labor costs account for about 42 pct of the total estimated milling cost; however, labor cost estimates range from 24 to 53 pct.

The 24 mills treating underground ore only for gold bullion production, using the Merrill-Crowe-zinc dust precipitation method for extracting gold from the cyanide solution, account for about 45 pct of total underground ore milling capacity. These 24 mills are, on average, about 43 pct larger in ore milling capacity than the 6 mills using carbon-in-pulp methods (1.83 million mt/yr versus 1.28 million mt/yr). Estimated operating costs for 22 of the 24 mills are not significantly different from the estimates for the CIP operations, with an average of \$5.94/mt ore milled and a range of \$3.21 to \$7.53. Labor cost estimates for these 22 mills range from about 30 to 52 pct of the total mill cost with an average of 42 pct. The two mills with relatively high costs (outside of what appears to be a normal range) include one that is very small in capacity and one that is very old.

Two mills float the tailings from the cyanide leach stage to produce pyrite concentrates for sale to nearby operations with acid plants that produce H_2SO_4 to be used in leaching for U_3O_8 production. These two mills account for only 4 pct of the total underground ore milling capacity and average about 1.8 million mt/yr. The estimated mill operating costs average \$6.10/mt ore milled, slightly higher than those operations that only produce gold bullion, with labor costs accounting for about 43 pct of the total milling cost. However, the small number of mills in this category and the expected range of error in the estimation method preclude making any definitive statements about the added costs incurred due to the flotation of tailings for pyrite concentrate production except that they are probably \$0.20/mt to \$0.50/mt ore milled.

The 11 operations producing both gold and uranium from underground ores present a special case for several reasons. First, if the installed circuitry used for treating the ore for gold recovery is counted as an individual "mill" that is separate and distinct from the circuitry treating ore for U_3O_8 recovery, then these 11 operations had a total of 38 separate mills in place as of 1983. Mills that are used only for gold leaching can be, and have been, converted from treating underground ore for gold production to treating underground ore or old tailings dams material for U_3O_8 production. However, the economics of the two commodities, Au and U_3O_8, are basically different, and the operations are set up to reflect those differences. Second, the estimated operating costs given in this study for the gold-uranium producers reflect all costs for cyanide leaching for gold bullion production and MnO_2-H_2SO_4 leaching for uranium production, any costs for flotation to produce pyrite concentrates, and costs of roasting of pyrite concentrates to produce H_2SO_4, if applicable. Third, some of these operations have their own pyrite flotation plants and acid plants, some have one or the other, and a few have neither a pyrite flotation plant nor an acid plant. For these reasons, a strict comparison of the estimated operating costs at the gold-uranium operations with those at operations producing only gold are not valid.

When uranium production from Witwatersrand Basin gold ores began in the early 1950's, the typical flowsheet involved cyanide leaching for gold bullion production and then vat leaching of the tailings from the cyanide leach with MnO_2 and H_2SO_4 for production of uranium hexafluoride. Because of the need for H_2SO_4 in the uranium vat leach, two problems immediately arose. First, the residues from the cyanide leach were highly alkaline and required a large amount of H_2SO_4 to lower the pH to an adequate level for pyrite flotation. Second, some of the ores that were high in U_3O_8 content were low in pyrite-sulfide content. Thus, over the years, three major developments have occurred at the gold-uranium operations in South Africa.

First, some operations have taken to floating the ore for pyrite concentrate production prior to the cyanide leaching for gold stage. In this case, the calcine residue from H_2SO_4 production is returned for cyanide leaching later. Second, some operations have chosen to use what is called the "reverse leaching" method, which simply means that the uranium leaching stage precedes the gold leaching stage. Third, some of the operations do not have a pyrite flotation plant or an acid plant because the pyrite content of their ore is not high enough. The shortfall in H_2SO_4 production is covered by those operations that do have high pyrite contents in their ores and produce more H_2SO_4 than their own internal needs require.

The 11 operations producing gold and uranium are located in 4 of the 7 gold mining districts on the Witwatersrand. Four are located in the Klerksdorp Goldfield, three are located in the Far West Rand Goldfield, and two each are located in the West Rand and Orange Free State Goldfields. Seven of the 11 operations have flotation plants, and 6 of the 11 have acid production facilities. As noted in table 24, these 11 operations have a combined total of 38 individual gold or uranium producing mills. Most of the operations treat the same underground ore twice for gold and uranium. Two of the operations have a fairly sizable capacity for treating old slimes dam material for gold and uranium production, and one operation has a large plant to produce only uranium from reclaimed slimes dam material. Only 2 of the 11 operations were using the reverse leach method at some or all of their mills in 1983.

The 19 gold mills at these 11 operations have a total capacity to mill 41.8 million mt underground ore, or about 43.5 pct of the total underground ore milling capacity that was analyzed. Individual mill capacities range from 630,000 to 3.1 million mt/yr with an average of about 2.2 million.

Table 24.—Summary of sand and slimes material available for reprocessing in South Africa

	Ore, 10^6 mt	Recoverable grade, g/mt	Recoverable gold, 10^6 tr oz
Total underground ore milled, 1885–1983	4,060	9.55	1,247
Demonstrated resource of low-grade material evaluated:			
Sands and slimes at 6 major reprocessing operations	1,164	.29	10.853
Sands and slimes at 10 underground operations	289	.18	1.672
Current tailings for reprocessing as of 1984	624	.08	1.605
Total or average	2,077	.21	14.06
Demonstrated resource[1] (not evaluated):			
Remaining sand and slimes[2]	2,600	.23	19.6
Potential future sand and slimes[3]	2,364	.10	7.6
Total or average	4,964	.17	27.2

[1]Estimates of remaining sand and slimes plus remaining current slimes.
[2]Total milled 1885–1983 minus demonstrated resource of sands and slimes analyzed at 6 major reprocessing operations (1,164 x 10^6 mt) and 10 underground operations (289 x 10^6 mt). Assumed 95-pct recovery of gold in initial milling, 50-pct recovery in reprocessing.
[3]In situ underground demonstrated resource as of 1984 minus tonnage being reprocessed as of 1983. Assumed recovery of 95.5 pct of gold in initial milling, 30 pct in reprocessing.

The 19 uranium mills at these 11 operations have a total milling capacity of about 2.4 million mt/yr.

As a group, the estimated operating costs at the 11 operations have a wide range, from $4.29/mt to $12.18/mt ore milled. This larger group can be split into two smaller groups for comparison. The first group would comprise the five operations that have their own pyrite and H_2SO_4 production facilities, and the second group would consist of the six properties that have either a pyrite production plant or an acid plant or neither. The first group has estimated operating costs ranging from $4.29/mt to $12.18/mt ore feed with an average of $9.13. The six operations in the second group have estimated operating costs ranging from $4.78/mt to $9.56/mt, with an average of $6.11. Labor costs in the first group range from 27 to 54 pct of the total mill operating cost with an average of 40 pct. Labor costs in the second group are markedly lower with a range of 23 to 38 pct and an average of 31.5 pct of total mill operating cost.

Low-Grade Milling

The last major milling category for discussion involves the various methods being used to produce gold, uranium, pyrite concentrate, and sulfuric acid from old sands and slimes dump materials left over from prior milling operations and from the reprocessing of the slimes from current milling operations. Basically, all of these operations can be combined under one major category broadly defined as low-grade milling.

As noted earlier, 2.077 billion mt of the total demonstrated resource evaluated in this study represents surface material (old sand dumps, old slimes dams, and current tailings) at an average recoverable grade of 0.21 g/mt. Table 24 contains data on the composition of this demonstrated surface resource. The resource is comprised of 1.164 billion mt at 0.29 g/mt recoverable gold at the six major reprocessing operations that have come into production since 1977; 0.289 billion mt at 0.18 g/mt recoverable gold contained in old dumps and dams at 10 of the major underground operations; and 0.624 billion mt at 0.08 g/mt recoverable gold contained in current mill tailings that are being reprocessed as of 1983 at the major operations.

These three sources, which comprise the demonstrated resource of surface material analyzed in this study, are the only material committed to reprocessing as of the early 1980's and contain an estimated 14.06 million tr oz of recoverable gold. Two additional sources that were not included in the analyzed demonstrated resource could account for close to 27 million tr oz of additional gold production in future years. These sources are (1) material in old sand and slimes dumps that was not committed to production as of 1982–83 and (2) the current slimes that will result from the milling of about 2.364 billion mt of the underground demonstrated resource and that were not committed to reprocessing as of 1982–83.

The six evaluated reprocessing operations split into three groups: those that produce pyrite concentrate along with gold bullion, those that produce only gold bullion, and those that produce gold bullion, pyrite concentrate, sulfuric acid, and uranium. Table 25 summarizes the breakdown of the six operations by products along with ore feed capacities and weighted-average feed grades. As shown, the three operations producing only dore bullion are relatively small with ore feed capacities ranging from 565,000 to 840,000 mt/yr and averaging 690,000 mt/yr.

All three of these operations are reprocessing only sand dump material grading 1.0 to 1.1 g/mt. The one operation producing a pyrite concentrate along with dore bullion is processing both sand dump material grading about 1.0 g/mt and slimes dam material grading close to 0.45 g/mt with high sulfur grades at 1.7 wt pct. At 6.58 million mt/yr, it is a much higher capacity operation than those that process only the higher grade sand dumps.

The largest capacity reprocessing operations are those that are treating only slimes material, either from reclamation of old dam material or from retreating the tailings from current milling operations. Because of the low grades of the feed material being treated (0.25 to 0.66 g/mt) and low gold recoveries (30 to 50 pct), these operations have to be large-scale, low-cost operations. They must rely heavily, if not predominantly, on the revenues from production of pyrite concentrates, sulfuric acid, and especially uranium. As of the early 1980's, uranium contents (U) in the feed were 46 to 107 g/mt, while sulfur (S) contents ranged from 0.7 to

Table 25.—Mill characteristics of six low-grade surface waste reprocessing operations in South Africa

Products	Number of operations	Operation capacities, 10^3 mt/yr		Weighted-average feed grade, g/mt
		Range	Average	
Pyrite concentrate and dore bullion	1	NA	6,580	0.59
Dore bullion only	3	565– 840	690	1.04
Dore bullion, pyrite concentrate, H_2SO_4, U_3O_8	2	19,200–23,400	21,300	.40

NA Not available.

1.0 wt pct. Recoveries of uranium were low (27 to 35 pct), and sulfur recoveries were fairly high (75 to 80 pct). Based on the data evaluated for this study, it appears that gold recoveries are 70 to 75 pct when retreating the higher grade sands (0.9 to 1.1 g/mt) but drop to 30 to 45 pct with the much lower grade slimes material (less than 0.40 g/mt).

The economics of the low-grade operations evaluated in this study are very precarious and in some cases are highly dependent on byproduct revenues. All of the operations have been brought into production since 1975, during the period of large increases in the price of gold. Yet, even if the economics of the low-tonnage milling operations were excellent and all of the possible materials were processed, they still would account for only about 40 million tr oz of total gold production over the next 25 to 40 yr. When compared with the recoverable gold in the demonstrated underground resource in South Africa (approximately 702 million tr oz), it can be seen that the overall importance of these retreatment facilities to long-term gold availability from South Africa is not significant.

A final comment should be made about the most pressing issue regarding gold milling in South Africa: labor productivity. With present practices, the primary gold mills of South Africa are very labor intensive relative to other gold mills around the world. If one uses a subset population of 20 of the 24 mills producing only gold with the Merrill-Crowe-zinc dust precipitation method, this study estimates that these 20 mills require approximately 25,134 employees to mill about 38.7 million mt/yr ore. If it is assumed that an average of 300 shifts are worked per employee per year, then the indicated productivity of the 20 mills is about 5.1 mt ore milled per shift. This productivity level is significantly lower than that of the lowest productivity vat leaching mills in the United States, which ranges from 10 to 20 mt per worker-shift.

It is very difficult to obtain a detailed breakdown of employment that is directly attributable to the milling stage at all of the South African gold mines. For that reason, the above estimates of South African mill labor productivity may be lower than actual productivity because they include workers who normally would not be accounted to the milling stage in other countries, such as the United States. Nonetheless, it is felt that this 5.1-mt-per-worker-shift productivity estimate is not more than 50 pct lower than what is actually the case. A major reason for the lower productivity is that a great deal of hand sorting of waste and ore is performed at South African gold mills, averaging 20 to 40 pct of the total material hoisted.

If a typical U.S. mining wage rate were applied to the employment levels in practice at the South African gold mills in the early 1980's, a rough indication is that a $6/mt mill operating cost would increase to about $19.41 owing to increased labor costs alone. However, in contrast to the same hypothetical situation posed in the mining section, the employment levels at South African gold mills are felt to be much more controllable due to technology.

Refining and Transportation

All of the gold products from the 44 operations evaluated in this study are in the form of gold-silver dore bullion. Typical South African dore bullions average 98 pct combined gold plus silver, with 2 pct base metals such as Cu, Pb, Zn, and Fe. Typical South African dore bullion is very high in gold content at about 87 to 94 pct gold with the silver content varying from 4 to 11 pct. All of the gold bullion produced in South Africa is refined at the Rand Refinery in Germiston, about 15 km south of Johannesburg. The refinery was first constructed in 1921 with an initial design capacity to refine 12.0 million tr oz/yr gold. The refinery was expanded until peak production of 32.395 million tr oz of fine gold was reached in 1970, at which time this single refinery produced approximately 75 pct of total MEC production of fine gold (*16*, p. 204). Extensively modernized in 1965 when it was nearly 40 yr old, the refinery is fully capable of handling any foreseen increase in production that may occur in South Africa.

The Rand Refinery Ltd. Corp. is a cooperative service company established for the gold mining industry of South Africa (*16*, p. 205). It does not purchase the bullions and other precious metal bearing materials from its members, but rather, processes them for the members. Thus, the costs of refining, insurance, and security are the only costs incurred by the member firms of the cooperative, which includes all of the major gold mining companies in South Africa. The Orange Free State Goldfield mines are the farthest distance from the Rand Refinery (250 km by road), the Eastern Transvaal mines are about 200 to 225 km by road from the Rand Refinery.

UNITED STATES

HISTORICAL PERSPECTIVE

Total mine production of gold in the United States from 1799 through 1983 is estimated at 335 million tr oz. It is further estimated that a rough breakdown of this total production into the three major ore sources would be as follows: primary gold deposits, lode mining—175 million tr oz (52 pct); primary gold deposits, placer mining—115 million tr oz (34 pct); byproduct gold deposits, lode mining—45 million tr oz (14 pct).

The earliest significant recorded gold find in the United States was made in Cabarrus County, NC, in 1798. A year later, gold was discovered in Stanley County, NC, and the first U.S. "gold rush" was underway. From 1799 through the 1840's gold was produced from placers and weathered bedrock in the Appalachian Mountain region, mostly from workings in northern Georgia and central-southcentral North Carolina. With the news of the discoveries in northern California in 1847–48 many of the gold miners in the Appalachian goldfields headed westwards, and eastern gold production dropped off.

The discoveries in northern California proved to be extremely rich, but by the late 1850's, the smaller placer claims had been worked out and laws governing mining by hydraulic methods had been passed. Thus, many of the "49ers" began to move into the interior of the Western United States in search of new goldfields. This migration resulted in the opening up of the Comstock Lode and Tonopah districts in Nevada in 1859 and 1860, the Clear Creek discovery in Colorado in 1859, and numerous other discoveries, mostly in Idaho and Montana, during 1861 through 1866.

Up to the early 1870's, most gold production came from easily mined placer deposits, but in the 1870's underground mining of lode gold deposits began to play a major role in the gold industry, especially in Colorado. This was a direct result of three major factors: the importation of experienced underground miners from the tin mines of Cornwall, England; the increased use of steam engines in mining; and the use of dynamite, which was invented in 1866. The decade of the 1870's was notable for the discovery of the famous Homestake Lode in South Dakota and the many gold and silver districts of Colorado. However, it was evident by the late 1870's that discoveries of major, new, unknown gold districts in the Western United States were becoming scarce. In the early 1880's the news of placer gold discoveries in Alaska began to draw attention; the first discoveries there had been made as early as 1848 on the Kenai Peninsula and in 1870 along the coast just south of the present city of Juneau.

Discussion of the historical significance of gold in the United States begins with the discoveries in California in 1847–49. This was the first find in the United States that was large enough in terms of new gold supply to affect the world's monetary system.

It has been estimated that average annual world production for 1840–49 (prior to the California discoveries) was only 1.76 million tr oz/yr, while average annual world production for 1850–59 (the time of major production in the California fields) was 6.4 million tr oz/yr (*4*, p. 29). This 366-pct increase in annual world production (4.5 million tr oz) can be assumed to represent production from California since the major Australian, South African, and Canadian discoveries either had not been made or were just being made at the end of the 1850's. This indicated level of annual production in the California fields during the 1850's was an enormous amount and meant that when the inevitable decline occurred in California, total U.S. production would likely decline in proportion. As mentioned, discoveries of new districts in Nevada, Colorado, Montana, and Idaho did occur during the 1860's and 1870's; however, these discoveries were insufficient to make up for the lost California production, and by 1890 total U.S. gold production had fallen to around 1.7 million to 1.8 million tr oz/yr (*17*, p. 265).

From 1890 to 1905, a sustained rise in annual gold production occurred in the United States with production reaching 4.6 million tr oz by 1906 (*18*, p. 580). About 1.0 million of this 2.8-million-tr-oz increase represented increased Alaskan production (mostly placer) during the great Alaskan "gold rush" (*19*, p. 35). The remaining 1.8 million oz of added annual production was mostly from "primary" gold operations and probably reflected both a maturation and further development of the fields discovered in the 1860's and 1870's. Additional production also came from small operations because of the fixing of the gold price, which legalized the free trade of gold and allowed currency transactions among nations to be settled in gold.

Figure 16 shows U.S. gold production by the three major ore sources from 1905 through 1983 (*20*). Several points of interest are—

1. The two precipitous drops in production, in 1915–20 and 1940–45, both correspond with major World Wars.
2. Placer production is no longer a significant factor in overall U.S. production of newly mined gold.
3. Production of gold from base metal ores (essentially byproduct gold production) has ranged from a low of 50,000 tr oz/yr in 1933 (the depth of the Great Depression) to highs of 600,000 to 750,000 tr oz/yr. The highest sustained production levels from base metal ores occurred during the period from 1947 through the 1960's. It appears that the base level of production during normal economic periods has been about 300,000 to 500,000 tr oz/yr gold, with 500,000 to 750,000 tr oz being produced during good economic periods.
4. Primary gold production since 1943 has never attained the high levels achieved by the many "small" operations in 1905–15 and 1935–44 because of social, political, legal, environmental, and market changes.

Figure 17 gives a breakdown of recent U.S. gold production for 1968–83. As shown in this figure, production from all three sources—primary lode, byproduct base metal, and primary placer deposits—steadily decreased from 1970 through 1979, with total annual mine production of gold in the United States falling 47 pct, from 1.7 million tr oz in 1969 to 920,000 tr oz in 1979. Primary lode production

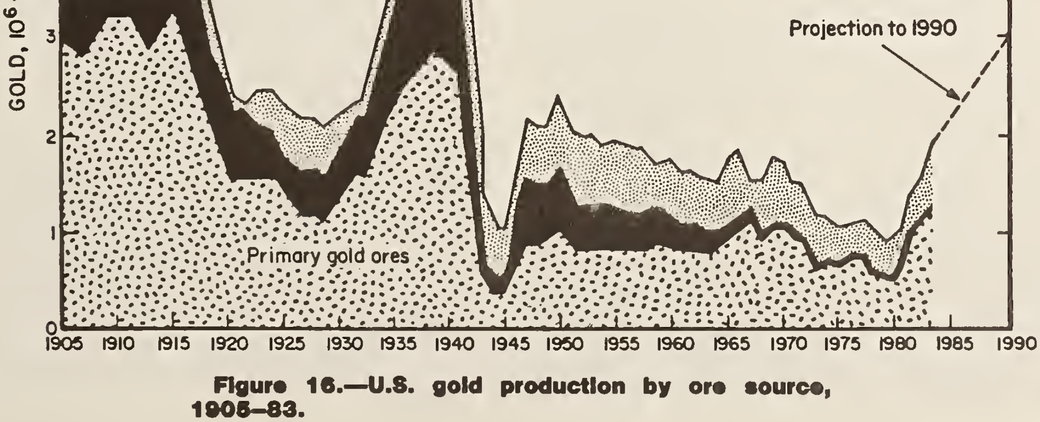

Figure 16.—U.S. gold production by ore source, 1905–83.

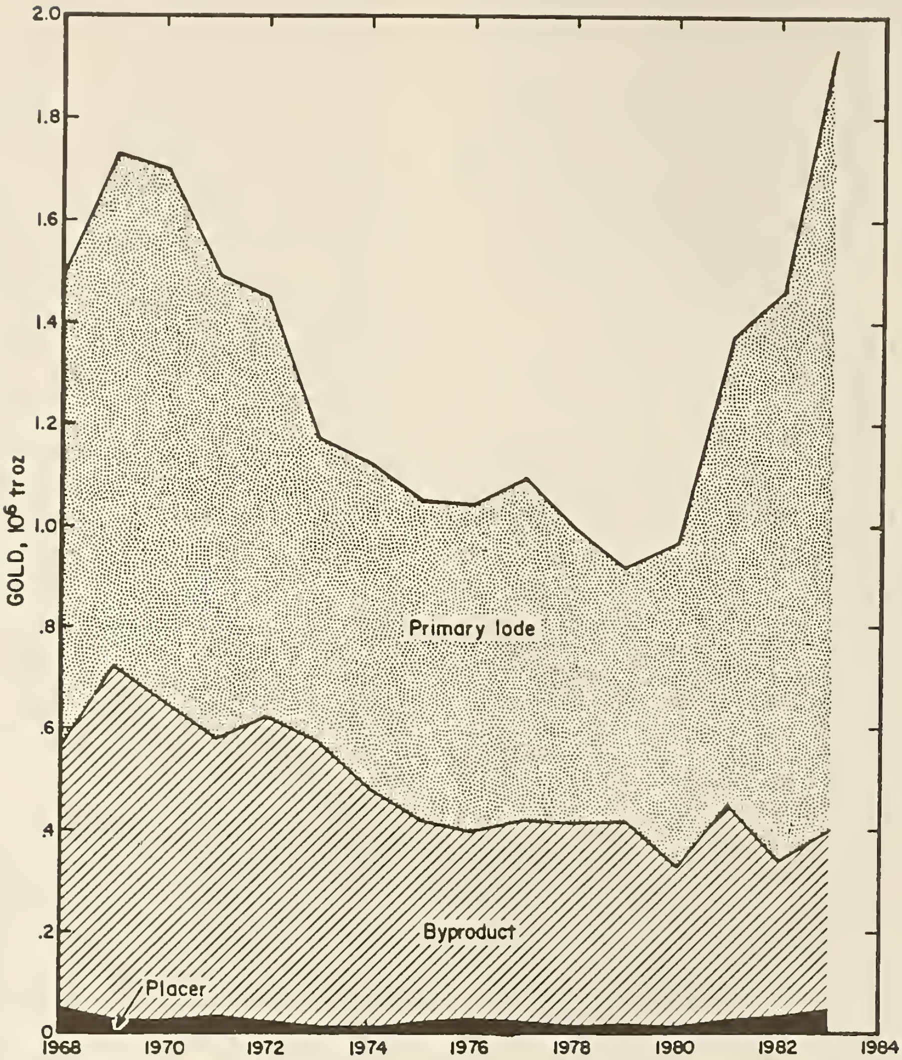

Figure 17.—U.S. gold production by ore source, 1968–83.

decreased the most, on a percentage basis, with a decline of 50 pct from 1.0 to 0.5 million tr oz. Byproduct gold production fell by 42 pct, from 693,000 to 400,000 tr oz, while placer production fell 33 pct, from 30,000 to 20,000 tr oz, over the same period.

Since 1979, U.S. gold production has increased every year, resulting in a 100-pct increase in annual production over the last 4-year period. The great majority of this increase has come from primary lode deposits since byproduct production from base metal deposits has declined. However, even after this doubling of gold production, 1983 output is still only 6.6 pct larger than 1969's level—despite 14 yr of exploration and development activities during a period when the price of gold increased nearly 900 pct in nominal terms and nearly 400 pct in real (1981 dollar) terms.

Placer production has enjoyed a modest increase during the 1980's, but placer production is not expected to comprise a substantial portion of total U.S. gold production given continuation of the current price level.

Byproduct gold production from base metal ores declined steadily from the late 1960's to the early 1980's. This decline, however, reflected a drop from an historically strong period of base metal production due to the boom period of the 1950's and 1960's, rather than a decrease from a "normal" level. The level of gold production from base metal ores has remained fairly constant between 300,000 to 500,000 tr oz/yr for the past 10 yr, a level very similar to that experienced during the early years of the 20th century. Also, for the past 10-yr period, average production has been about 400,000 tr oz/yr, which compares with an average of 450,000 tr oz/yr over the last 80 yr.

For the foreseeable future, it is expected that the level of gold production from byproduct ores in the United States should range between 300,000 to 500,000 tr oz/yr, but a strong resurgence in domestic copper production could result in a range of 500,000 to 700,000 tr oz/yr by the year 2000. These predictions are highly dependent upon the prospects for the U.S. copper industry, which has typically accounted for 83 to 87 pct of byproduct gold production for the last 15 yr. This industry is presently under severe economic pressure, and future production potential remains uncertain.

RESOURCE OVERVIEW, 1984

All of the largest and most significant primary gold producers in the United States, as of January 1984, were subject to a complete geologic, engineering, and economic cost evaluation in this study. This study defined 17 primary gold mining operations in the continental United States that were in production during 1983 and that represented in excess of 90 pct of total primary gold output. One of the operations closed down in late 1983 and was not subject to futher cost or availability evaluation. The 16 primary gold producers in the continental United States as of 1984 are listed in table 26. Figures 18 through 20 show the locations of the 16 major producing operations, prospective gold mines, and areas of primary gold deposits.

In 1981, six primary copper operations producing gold as a byproduct were ranked among the top 25 U.S. gold producers. As of 1983, three of these six byproduct gold producers had closed down indefinitely owing to depressed copper prices. The largest byproduct gold producer (Bingham Canyon, UT) has significantly reduced production, also indefinitely.

During 1981, two primary lead-zinc mines producing gold as a byproduct also ranked in the list of top 25 producers. By 1983, one of these mines had also closed indefinitely. Because of the very uncertain future of U.S.

Table 26.—Distribution of 16 major primary gold producers in the continental United States, by State and type of mining

State and Operation	Type[1]
Colorado: Victor Project	S
Idaho: West End-Garnet Creek	S
Montana:	
Golden Sunlight	S
Zortman-Landusky	S
Nevada:	
Alligator Ridge	S
Battle Mountain	S
Borealis	S
Carlin	S
Jerritt Canyon	S
Pinson-Preble-Ogee	S
Round Mountain	S
Windfall	S
New Mexico: Ortiz	S
Utah: Mercur	S
California: Yuba Placer	SD
South Dakota: Homestake	U

[1]S–surface, SD–surface (dredging), U–underground.

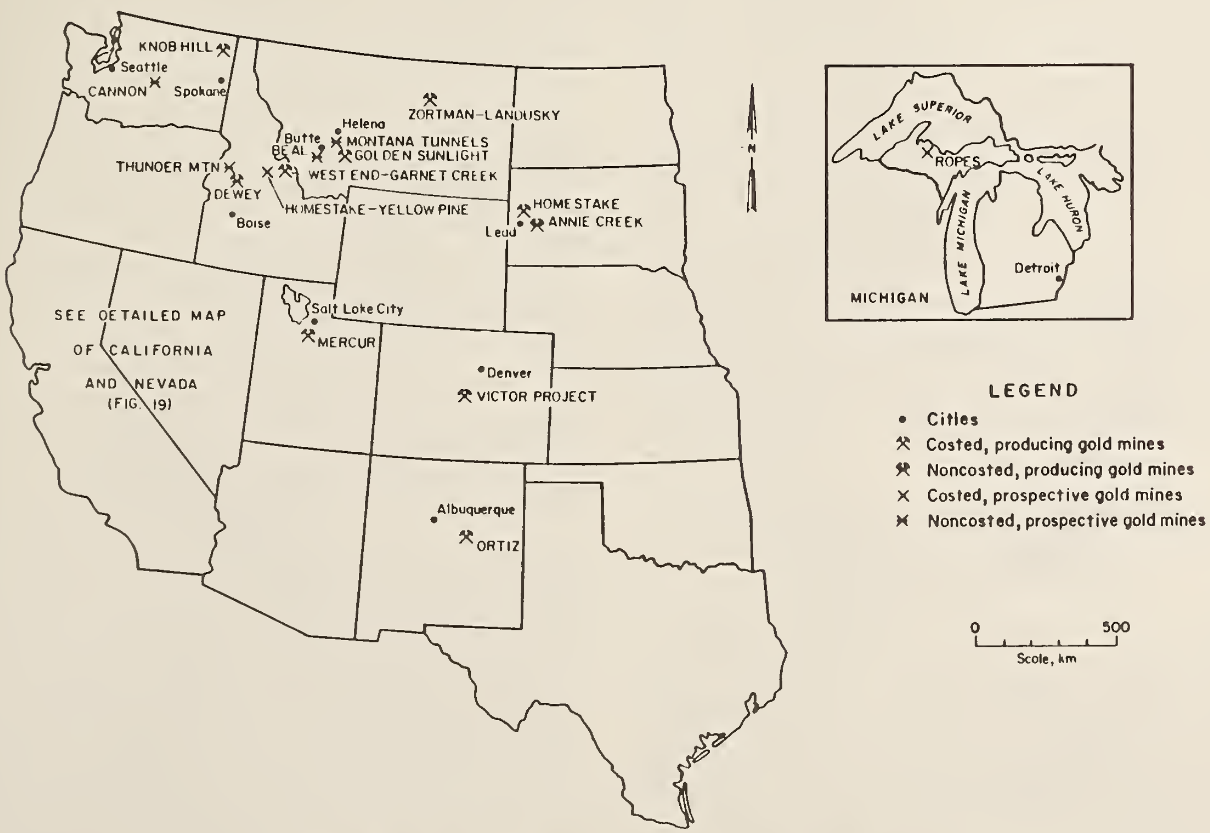

Figure 18.—Location of producing and prospective gold mining operations in the continental United States.

Figure 19.—Location of producing and prospective gold mining operations in California and Nevada.

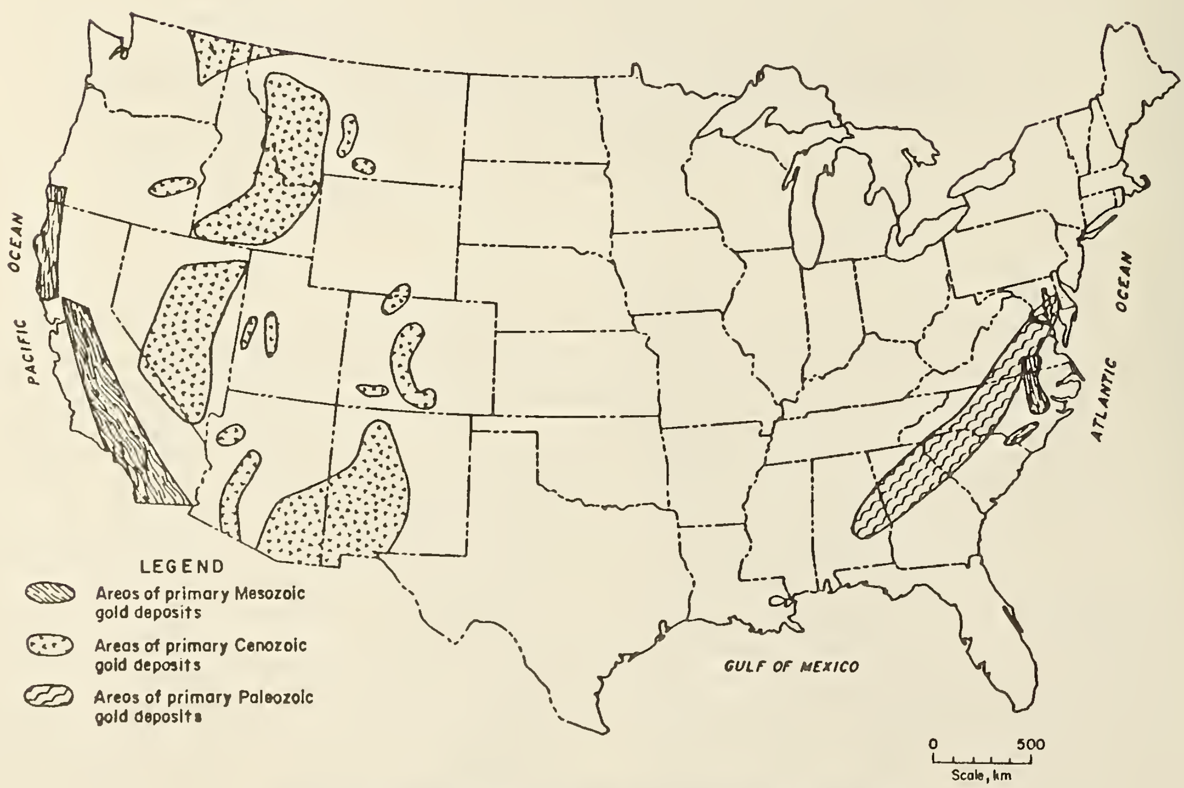

Figure 20.—Areas of primary gold deposits in the continental United States.

Table 27—Gold resource data for selected primary gold mines and deposits in the continental United States as of January 1984

Classification	Number of properties	Demonstrated resource[1]		Contained gold[1]		Recoverable gold	
		10^6 mt	Share, pct	10^6 tr oz	Share, pct	10^6 tr oz	Share, pct
Major producing operations:							
Surface	15	647	93	29.0	77	21.6	73
Underground	1	48	7	8.5	23	8.0	27
Total	16	695	100	37.5	100	29.6	100
Other mines and deposits:[2]							
Costed:							
Surface	5	65.5	96	5.13	93	4.47	93
Underground	1	2.5	4	.37	7	.33	7
Total	6	68	100	5.5	100	4.8	100
Noncosted[3]	18	NM	NAp	9–12	NAp	NM	NAp
Total	24	NM	NAp	14.5–17.5	NAp	NM	NAp
Grand totals:							
Demonstrated (costed)	22	763	NAp	43	NAp	34.4	NAp
Demonstrated plus noncosted	40	NM	NAp	52–55	NAp	NM	NAp

NAp Not applicable.
NM Not meaningful.
[1]Mill feed basis, includes adjustments for mining recovery and dilution.
[2]For detail on names and production status, see table 32.
[3]Not subjected to complete demonstrated resource and long-term total cost evaluation

copper producers and to a lesser extent lead-zinc producers, and because gold production from these mines is a result of base metal mining itself and not a driving cause, no further attempt was made to address the potential availability of byproduct gold production from copper or lead-zinc mines. All significant domestic copper and lead-zinc producers have been evaluated in detail in other MAP appraisals (*21-22*).

The 16 major primary gold producing operations in the continental United States as of 1984 represent at least 38 individual deposits. This is because 10 of the 16 operations are mining or will mine from 2 to 5 individual deposits over the life of the operation as defined by the current level of demonstrated resources.

Table 27 provides aggregate resource data for the 16 major producing operations and for 24 other properties (figures 18 and 19 show locations) that are either nonproducing, developing, or in the early stages of production. The resource data for the 16 major producers were estimated at the demonstrated level. The 24 other properties that are included are those considered as the most likely candidates for full development during the 1984–90 period. Six of these 24 properties were subject to complete demonstrated resource and cost evaluation to determine the near-term economics of new gold production in the United States. For the 18 noncosted properties, the estimates of contained gold are presented as a range to indicate the lower level of probability that is attached to them in the absence of a complete demonstrated resource evaluation.

In total, primary recoverable gold resources in the continental United States as of January 1984 are estimated to range from 43 million tr oz demonstrated resource contained in 16 producing and 6 nonproducing operations to as high as 55 million tr oz if the 18 noncosted properties of significance are included.

The great majority (93 pct) of demonstrated resource (mill feed) in the 16 major producing operations is surface-minable ore. Only 7 pct occurs as underground ore. Higher ore grades and recoveries for the underground resource result in 27 pct of total recoverable gold being represented by underground ore. Still, the majority of recoverable gold represents a surface resource. Of the six costed nonproducers, only one is a potential underground mine; it represents 7 pct of the contained and recoverable gold in this category. The United States is expected to remain highly dependent upon surface-minable gold resources.

Primary gold resources in Alaska, contained within 16 known, relatively major (mostly placer) operations of intermittent production status, are estimated to be 4 million tr oz, a probability of 50 pct is attached to this difficult-to-ascertain figure. Byproduct gold resources in all of the United States may be as high as 20 million tr oz, with roughly half of this total contained in the Bingham Canyon Mine in Utah. Total U.S. gold resources, therefore, from both primary and byproduct sources, are estimated to range from a high-probability (demonstrated) estimate of 43 million tr oz in 22 major primary properties to a lower probability estimate of 79 million tr oz if all known primary and byproduct sources of significance are included, regardless of production status. An independent estimate by Homestake Mining (*23*) places primary gold resources in the United States (assumed to include Alaska) at 69 million tr oz. This estimate includes all major producers and well over 100 explored prospects. The difference between this study's potential primary gold resource estimates and the Homestake estimate is due entirely to a difference in definition concerning which properties and how many properties to include in the total estimate. Interestingly, the percentage split between gold contained in surface and underground ore is the same, even though the Homestake estimate includes many more surface properties and a higher estimate of gold resources at the Homestake underground mine at Lead, SD.

As a final note, given that large areas of Alaska and the Western United States have not been thoroughly explored for their gold potential, it is felt that gold resources could be as high as the 100-million-tr-oz level published by Lucas (*1*). This rounded figure is considered to be an inferred upper range. In contrast, the resource data herein reported on and evaluated are "locateable" by known deposit and/or operation.

TOTAL GOLD AVAILABILITY AND PRODUCTION COST EVALUATION: 16 MAJOR PRODUCERS

The 16 major producers account for over 90 pct of all primary gold production and a majority of total production in the United States as of 1983. As shown in table 27, these 16 operations in total contain an estimated 695 million mt of demonstrated resource (mill feed) which contains 37.5 million tr oz of gold. As of January 1984 there is an estimated total refined gold availability of 29.6 million tr oz contained within all 16 operations. The five largest operations (Homestake, Carlin, Round Mountain, Battle Mountain, and Jerritt Canyon) contain 83 pct of the total recoverable gold. These same five operations, not surprisingly, account for at least 50 pct of total annual primary

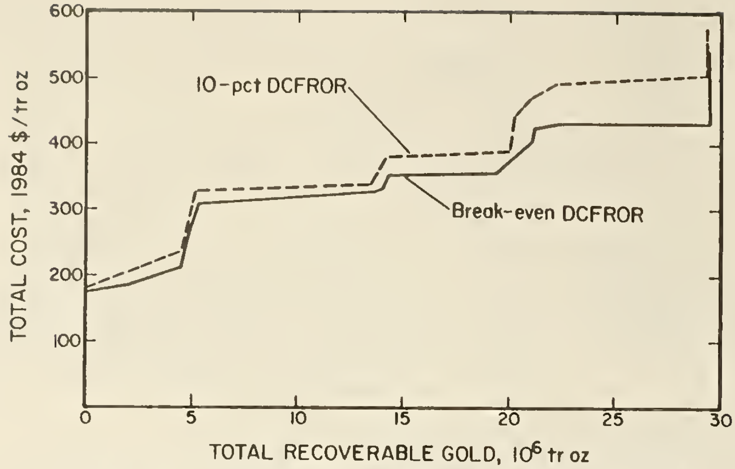

Figure 21.—Potential total U.S. gold available at various production cost levels from 16 major producers as of January 1984.

Table 28—Supporting data for figure 21; total gold potentially available from 16 major producing operations in the continental United States

	Break-even DCFROR		10-pct DCFROR	
Cost or price level, per troy ounce	Available gold, 10^3 tr oz (cumulative)	Number of mines (cumulative)	Available gold, 10^3 tr oz (cumulative)	Number of mines (cumulative)
$200 or less	2,311	2	162	1
$300 or less	4,957	4	4,957	4
$400 or less	20,140	11	20,140	11
$500 or less	29,556	15	22,313	14
Over $500	29,594	16	29,594	16

DCFROR = discounted cash flow rate of return.

gold production. The six costed nonproducers are estimated to have potential recoverable gold totaling 4.8 million tr oz.

Figure 21 and table 28 present the total gold availability estimates and long-run total cost determinations for the 16 major producers. Long-run production costs were determined at the break-even (0 pct) and 10-pct rate-of-return levels. Fully two-thirds of the total gold is available from 11 operations at a cost-price level of $400 or less. These 11 operations (10 surface and 1 underground) are able to realize a long-run rate of return of at least 10 pct given a gold price of up to $400/tr oz.

Only four operations can break even at a cost-price level of $300/tr oz or less; these same four can realize at least a 10-pct long-run rate of return at the $300 cost-price level. Fifteen operations can break even, and 14 can realize at least a 10-pct long-run rate of return, at a long-run cost-price level of up to $500/tr oz.

The profitability of the 16 major producers and the 6 costed nonproducers is also demonstrated by the data of table 29, which contains rate-of-return determinations at constant-dollar gold prices of $400/tr oz and $500/tr oz. At a constant-dollar gold price of $400, 11 current producers have profitable rates of return ranging from 13.5 pct to over 120 pct. None of the six costed nonproducers is profitable at a constant-dollar gold price of $400/tr oz given the criteria of this analysis (i.e., more than a 10-pct ROR).

At $500/tr oz, 14 of the major producers and 3 of the nonproducers are profitable. One producer (surface mining) and three nonproducers (two surface and one underground) require constant-dollar gold prices in excess of $500/tr oz to be profitable according to the criteria of this analysis. The three nonproducers that are not profitable at $500/tr oz all have long-term operating cost estimates above $350/tr oz recovered gold. The three nonproducers that are profitable at $500/tr oz (all surface operations) have operating costs below $250/tr oz recovered gold. The weighted-average operating cost for all five surface nonproducers that were cost-evaluated is estimated at $254/tr oz recovered gold; not suprisingly, the profitable operations are those with costs below the average, while the nonprofitable operations have costs well above the average.

Table 29.—Long-run DCFROR for selected U.S. gold properties, determined at $400 and $500 per troy ounce gold, $10 per troy ounce Ag, and a 10-pct discount rate

Gold price, per troy ounce	Number of operations	DCFROR range,[1] pct
	16 PRODUCERS	
$400	11	13.5–120.0
	5	.0
$500	14	11.0–120.0
	2	.0– 9.8
	6 NONPRODUCERS	
$400	6	0.0– 7.4
$500	3	12.5– 15.0
	3	4.0– 8.0

[1]The economic model does not calculate rates of return below 0 or above 120 pct.

Given current (late 1984) gold prices below $350/tr oz, all six of the evaluated nonproducers have long-run cost levels, over the life of the operations, that would result in real economic losses, especially given that typical mine lives

Table 30.—Comparative summary results of 1984 long-run cost determination analyses for producing and nonproducing surface operations in the continental United States

	Nonproducing (5 operations)		Producing (15 operations)	
	Range	Weighted average	Range	Weighted average
Operational data:				
Mill feed grade[1] ... g/mt	2.0 – 4.8	4.0	0.8 – 7.9	2.2
Average annual output ... 10^3 tr oz	10 – 125	NAp	6 – 268	NAp
Total recoverable gold[2] ... 10^3 tr oz	94 – 2,628	NAp	38 – 7,243	NAp
Producing years from Jan. 1984 for 60 pct of the operations	7 – 10	NAp	3 – 10	NAp
Capital and operating cost data:				
Total capital investment[3] ... 10^6 dollars	$6 – $165	NAp	$5 – $356	NAp
Capital cost per troy ounce	$63 – $96	$75	$21 – $126	$47
Operating cost[4] per troy ounce	$175 – $370	$254	$117 – $401	$271
Total operating plus capital cost per troy ounce	$271 – $445	$329	$152 – $527	$318
Long-run total cost per troy ounce:				
Break-even (0-pct DCFROR)	$329 – $458	$351	$173 – $538	$354
10-pct DCFROR	$449 – $577	$468	$180 – $567	$396

NAp Not applicable.
[1]Mill feed grades for each individual property are weighted-average grades of the entire demonstrated resource minable over the life of each operation. These individual property grades are then weight-averaged over each subgroup for comparison.
[2]Refined gold estimated to be recoverable as of Jan. 1984.
[3]Unrecovered capital investment in mine and mill plant and equipment, infrastructure, and development remaining as of Jan. 1984 plus reinvestments through life of operation.
[4]Mining plus milling cost per troy ounce of refined gold.

average only 5 to 8 yr. One possible exception is the McLaughlin operation in California, which has an initial 20-yr life, large planned annual capacity, and hence the potential to alter its mining and development plans to accommodate depressed prices, at least during the near term. For current producers, the maintenance of a $350 gold price would place 9 of the 16 operations (including 6 heap leaches) in a position of suffering a real economic loss and possible eventual closure. This could reduce expected average annual output by the late 1980's by up to 50 pct. In addition, current (late 1984) gold prices have at the very least delayed the eventual development of many of the 24 nonproducing properties included in this discussion, including 5 of the 6 nonproducers that were cost-evaluated.

The following section continues with an in-depth analysis of the comparative economics of current surface producers versus potential or developing surface mines.

Comparative Long-Run Total Production Costs

Table 30 contains economic summary data for the 15 surface producing and 5 surface nonproducing operations that were evaluated to determine comparative economics of new gold production in the United States. The five nonproducing surface operations are believed to adequately cover the range of most prospective future producers. In addition, the estimated average mill feed grades, productive lives, and capital and operating costs per ounce of recovered gold fall within the ranges established by the 15 major surface producers. These new operations are, in effect, a replacement resource similar to that being currently mined.

The major difference between current and prospective producers lies in total capital investments. For the nonproducing properties, total capital investments, by necessity, include the costs of initial development, construction, and purchase of new plant and equipment and related infrastructure, as well as the estimated costs of capital reinvestments over the life of the operation. These costs range, in total, from $6 million to $156 million for the development of surface mines capable of producing between 10,000 and 125,000 tr oz/yr gold. The majority of new surface mines (three of the five in this sample) will have annual outputs below 50,000 tr oz/yr and total capital investments below $50 million.

For current producers, the major initial capital investments have mostly been recovered through past production by 1984. Most of the capital costs remaining are those associated with future reinvestments or expansions to capacity. The most notable example of expansion is the Carlin operation in Nevada, where the Gold Quarry deposit is undergoing full development. The initial cost to fully develop this deposit is estimated to exceed $130 million in January 1984 dollar terms. Eleven of the 15 producing operations have total required capital investments and reinvestments as of January 1984 below $50 million.

Of particular interest is the fact that even though the five nonproducing operations range from 10,000 to 125,000 tr oz potential annual output, requiring between $6 and $165 million to fully exploit, capital costs on a per ounce of recoverable gold basis fall within the narrow range of $63/tr oz to $96/tr oz. This range probably represents an economic threshold of expected per-ounce capital costs for the development of new surface gold mines in the United States. Any prospective operation that falls significantly above the upper limit of this range will be less attractive for development (especially given that a majority of total capital investment is made prior to production) unless there is an expectation of a compensatingly lower than average per-ounce operating cost. Operating costs for both groups, however, show wide variation between operations, even those of similar size. This is not surprising given that each mine has unique characteristics regarding its geologic or technical and operational parameters.

The difference between total capital plus operating costs per ounce of recoverable gold and the break-even cost-price level is greater for current producers owing primarily to greater tax liabilities. Total break-even production costs for the 15 surface producers range from $173/tr oz to $538/tr oz. This range encompasses that derived for the nonproducers; as a result there is no significant difference between the two groups in terms of the weighted-average long-term total production costs at the break-even level.

A significant difference in total production costs is evident between the two groups at the 10-pct profitability level. All five of the nonproducers require 1984 constant prices exceeding $449/tr oz to obtain this prespecified rate of return. This large increase in required price is a result of the requirement to recover larger total and per-ounce capital costs in less time, and for some, over smaller annual production levels.

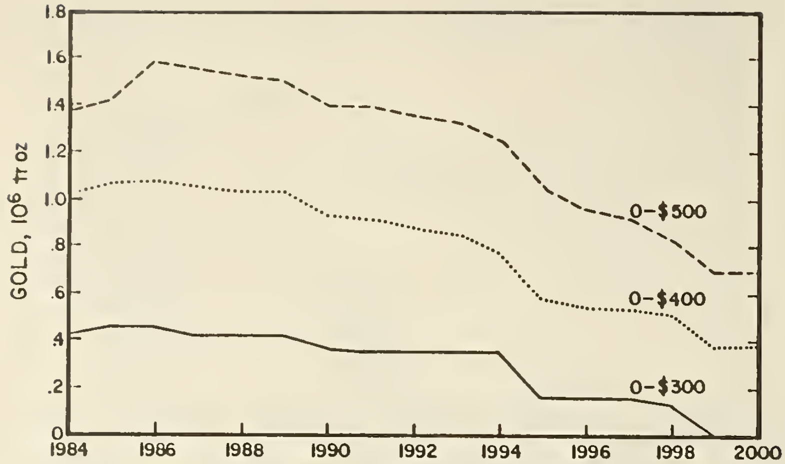

Figure 22.—Potential annual U.S. gold production available at various break-even production cost levels from 16 major producers as of January 1984.

Annual Production Potential Through 2000

As noted previously, the United States is heavily dependent upon surface mining for maintaining gold production. On a relative, worldwide basis, surface primary gold mines in the United States (both current producers and those awaiting or under development) are generally low-grade, short-life operations with annual outputs in the 20,000- to 90,000-tr-oz-range. There are notable exceptions such as the Jerritt Canyon, Round Mountain, Battle Mountain, Carlin, and McLaughlin operations. These five operations each produce or will produce in excess of 100,000 tr oz/yr gold and have *remaining* productive lives (based on current demonstrated resources) extending at least through the mid-1990's; three of the five operations are expected to produce beyond the year 2000. By contrast, the majority of the remaining producing and developing mines, as well as those considered most likely for development during this decade, generally represent annual production below 60,000 tr oz and have remaining or expected productive lives of 5 to 10 yr. Thus, the United States, unlike Canada or South Africa, will have to replace a large part of its demonstrated resources every 8 to 10 yr to maintain current production levels.

This section details expected annual production through 1990 for the 16 major evaluated primary gold producers (as of the reference point January 1984) and incorporates estimated annual output from those operations that are currently under development or in the early stages of production and those that are considered the most likely candidates for development. Two caveats are necessary. First, with a large number of small, short-life operations continually coming into and going out of production, it is very difficult to forecast potential output in any given year. Second, estimating output for developing or potential operations by necessity involves margins of error because development plans may change, be delayed, or be canceled altogether. This has become especially true during the last few years as gold price increases have failed to live up to the expectations of 1979–80. The purpose of this exercise is not to prophesy but rather to indicate the direction of future events given current information. The authors do not feel that the margins of error inherent in this type of analysis are significant enough to violate the basic trends and implications.

Table 31.—Potential annual production estimates for 16 major primary gold producers in the United States

Year	Number of producing operations	Total potential annual production, 10^3 tr oz
1984	16	1,378
1985	16	1,425
1986	16	1,585
1987	15	1,555
1988	15	1,528
1989	15	1,506
1990	13	1,398
1992	11	1,352
1994	9	1,252
1996	7	957
1998	4	830
2000	3	700

Figure 22 and table 31 present estimates of long-run break-even total production cost and annual gold availability, covering 1984 through 2000, for the 16 major producing operations that were evaluated. In the case of the Carlin operations in Nevada, the developing Gold Quarry deposit is included as part of the overall ongoing operation and not as a separate developing deposit.

During 1984–90, annual primary gold output from these 16 operations is estimated to increase from 1.378 million tr oz in 1984 to 1.585 million tr oz in 1986 and then decline to 1.398 million tr oz by 1990. During this 7-yr period, three operations (two heap leaching and one conventional surface) are expected to have ceased production. Also during this time, the large Gold Quarry deposit of the combined Carlin operations is expected to reach capacity production, which will add around 150,000 tr oz/yr to total output. The additional output from the development of Gold Quarry will compensate for the three smaller operations that are expected to be fully exploited by 1990.

During the period 1990–2000, total production is expected to further decrease as current demonstrated resources are depleted. In the absence of additions to demonstrated resources, 10 more operations are expected to close by the year 2000, leaving 3 of the 16 current producers still active after that time. Total production in 2000 from these three large operations will still represent 51 of 1984 production. This illustration underscores a basic characteristic of the U.S. gold mining industry: Most of the operations are small and their lives are relatively short,

Table 32.—Operations considered possible or probable producers during 1984–90

State and operation name	Mining method and ore type[1]	Status	Estimated annual capacity, 10^3 tr oz	Estimated first full year of production
NEAR-TERM PRODUCERS AND PROSPECTS				
California:				
Gray Eagle	OP milling ore	Initial production 1983	40	1984.
Jamestown	..do	Developing 1984	120	1985.
Mesquite	OP heap leach	Development decision expected late 1984.	80	1988.
Rich Gulch	OP milling ore	Feasibility study completed in early 1984.	100	1986.
Idaho:				
Dewey	..do	Initial production 1983, expanding 1984.	36	1984.
Thunder Mountain	..do	Feasibility study underway 1984.	25	1988.
Montana:				
Beal	..do	Feasibility study underway 1984.	45	1986.
Montana Tunnels	..do	..do	55	1987.
Nevada:				
Buckhorn	OP heap leach	Initial production mid-1984.	30	1985.
Dee (Boulder Creek)	..do	Developing 1984	30	1988.
Horse Canyon	..do	Initial production late 1983.	35	1984.
Paradise Peak	OP milling ore	Feasibility study underway 1984.	90	1986.
Relief Canyon	OP heap leach	Developing 1984	25	1985.
Ruby Hill	UG milling ore	Feasibility study stage 1984.	36	Post-1987.
Santa Fe	OP heap leach	Feasibility study underway 1984.	30	1987.
Sumich	UG milling ore	Developing 1984	30	1988.
South Dakota: Annie Creek	OP heap leach	Nominal production late 1983.	20	1984.
Washington: Cannon	UG milling ore	Developing 1984	140	1985.
Subtotal (rounded)	NAp	NAp	970	NAp.
EVALUATED FOR LONG-TERM PRODUCTION COSTS				
California:				
McLaughlin	OP milling ore	Developing 1984	130	1985.
Royal-Mountain King	..do	Feasibility study stage 1984.	44	Post-1986.
San Juan Ridge	..do	Developing 1984	40	1986.
Idaho: Homestake-Yellow Pine	..do	Explored deposit	90	Post-1987.
Michigan: Ropes	UG milling ore	Developing 1984	22	1987.
Nevada: Goldfield Project	OP heap leach	Feasibility study stage 1984.	12	Post-1986.
Subtotal (rounded)	NAp	NAp	340	NAp.
Grand total (rounded)	NAp	NAp	1,310	NAP.

[1]OP—open pit, UG—underground.

which means that the resource base must be constantly replaced to maintain current output levels.

Table 32 lists 24 operations that are either developing or considered probable for development between 1984 and 1990. With only one exception, the list was held to the criteria of (1) there is at least 20,000 tr oz annual production potential, (2) the property is at least in the feasibility study stage, and (3) there is an initial demonstrated resource sufficient for at least 5 yr of production. A tabulation that employed more liberal production, resource, or development progress criteria, and that included all explored prospects for which published information is available, could easily list more than 100 properties.

These 24 operations, in total, represent approximately 1.31 million tr oz of additional annual production capacity that could potentially come on-stream between 1984 and 1990 if all 24 were indeed developed. Sixteen of the 24 operations, representing approximately 1.0 million oz/yr (75 pct of the total estimated annual production potential), are considered highly probable near-term producers. It is important to stress that 20 of the 24 operations would be surface producers, which implies that the United States will continue to remain dependent upon surface mining for a majority of its gold production. Also, at least one-third of the operations will employ heap leaching. Total production costs for these 20 surface operations, in general, should not be significantly different from those of current surface producers.

The information of tables 31 and 32 is combined in table 33 to arrive at estimates of potential total annual gold production between 1984 and 1990, assuming constant byproduct and placer gold production based upon the 1977–83 period. No attempt was made to estimate potential future byproduct gold production, the majority of which emanates from copper mines, given the very uncertain outlook of the U.S. copper industry. Similarly, no attempt was made to estimate potential future placer production given that the percentage contribution of placer production is very low, usually around 2 pct.

Table 33.—Potential annual U.S. gold production circa 1990, by type of operation

Type of operation	*Total or range, 10^3 tr oz*
Primary:	
Major producers as of January 1984	1,400
Developing, in early stage of production, or considered probable for development as of circa 1984:[1]	
Possible	1,310
Probable	1,000
Placer[2]	20 – 30
Base metal (byproduct gold)[2]	300 – 400
Totals:	
Possible	3,140
Probable	2,700

[1]Restricted to properties with annual production potential of at least 20,000 tr oz that are at least in the feasibility stage, and that have a demonstrated resource sufficient for at least 5 yr of production.
[2]Assumed to remain constant at 1977–83 average levels.

As shown in table 33, output by 1990 is expected to approximate 2.7 million tr oz, assuming that the 1.0 million tr oz of new production considered highly probable is developed and output of current producers is maintained. If all 24 operations are developed, then total output could approximate 3.1 million tr oz. It must be remembered, however, that this would be a "best case" scenario in terms of the price of gold and the results of feasibility studies and future developments.

PRIMARY GOLD MINING IN THE CONTINENTAL UNITED STATES

The 16 major gold producing operations in the continental United States as of January 1984 can be classified into three basic types: 14 surface (bench-berm), 1 floating plant-dredging operation, and 1 underground mine. Separate discussions of the three major mining types follow.

Surface Mining

Of the 14 producing surface operations evaluated as of January 1984, only 2 were in production in 1968 and only 5 were in production as late as 1979. Thus, two-thirds of the major surface mines have been brought on-stream in the last 5 yr. Six of these nine new operations, and 8 of the 14 in total, utilize heap leaching of the ore, rather than conventional milling. In terms of ore grades, the eight current heap leaching operations are treating material grading from 1 to 5 g/mt with a straight average of 2.5 g/mt, while the six operations milling their ore are treating material ranging from 1.7 to 7.9 g/mt with a straight average of 5.3 g/mt. From a long-term availability perspective, only 3 of the 14 operations will be treating 100 pct millable ore over their entire productive lives, since 2 of the 5 that are currently milling their ore have at least some portion of their long-term resource planned for heap leaching.

Table 34 presents combined operational data for the 14 major surface mines. Included are estimates, circa 1982–83, of mining labor levels (including prorated administrative employment), ore capacity, waste capacity, ore plus waste capacity, waste to ore ratios, mine productivity (defined as metric tons of ore plus waste per worker-shift), and estimated gold output for 1983. Table 34 demonstrates two major points concerning the surface mining of gold ores in the continental United States as of 1983. First, the evaluated mines are highly efficient, with an average productivity measure of 238 mt ore plus waste being mined per worker-shift. Second, the weighted-average recoverable grade of the ore mined, estimated to be slightly less than 3 g/mt, is relatively low. Both of these characteristics are due to four major technological and economic developments since the early to mid-1970's, as follows:

1. The availability of larger and more efficient earthmoving equipment.
2. The major increase in the price of gold.
3. The development of and refinements to the heap leaching method of gold extraction.
4. The development of and refinements to the various techniques of extracting gold by the use of carbon.

It is difficult to ascertain general characteristics of the surface mining operations analyzed in this study. Stripping ratios vary between operations, and even within an operation, as do the ore and the waste haulage distances. These two items, especially the stripping ratio, depend more upon the gold grade of the defined ore reserve and can vary from year to year depending upon the price of gold. An operation will attempt to adjust to the type of resources that is available.

As analyzed, the stripping ratios for the operations range from 1.0/1.0 to 9.8/1.0, the haulage distances for ore range from 0.3 to over 12 km, and the transport distances for waste range from 0.3 to 1.5 km. Over their estimated productive lives, the 14 surface mining operations will mine from as many as 35 different pits (deposits).

Table 34.—Combined operational data for major gold producing surface mines in the continental United States

Category	*Value*
Total estimated employment in mining[1]	1,100
Annual ore capacity[2] .... 10^6 mt	14.3
Annual waste capacity[2] .... 10^6 mt	51.2
Total annual ore plus waste capacity[2] .... 10^6 mt	65.5
Overall waste-ore ratio, weighted average[2]	3.6:1.0
Overall productivity, ore plus waste per worker-shift[3] .... mt	238
Estimated 1983 gold output .... 10^3 tr oz	1,350
Estimated recoverable gold grade[4] .... g/mt	2.94

[1]Includes prorated administrative labor; circa 1982–83 estimates.
[2]Circa 1982–83.
[3]Includes prorated administrative labor.
[4]Circa 1983 ores.

Table 35.—Comparative operational characteristics of continental U.S. surface mines, low and high mining cost levels

Operational characteristics	Low-cost mines	High-cost mines
Number of operations	9	5
Ore plus waste moved .... 10^6 mt/yr	4.5–14.0	0.30–2.5
Overall mining productivity, average per shift[1] .... mt	290	170
Operations using contract mining:		
Number	1	3
Percent	11	60
Operations employing heap leaching:		
Number	3	5
Percent	33	100
Typical excavation equipment:		
Operations using shovels and front-end loaders:		
Number	7	1
Percent	78	20
Operations using front-end loaders only:		
Number	2	4
Percent	22	80
Shovel size .... m³	3.8–8.0	4.0
Front-end loader size .... m³	4.6–10.0	3.8–5.3
Typical transport equipment:		
Average number of trucks per operation	12	8
Truck size .... mt	45–77	30–45
Operations using crawler tractors with trailers:		
Number	0	1
Percent	0	20

[1]Metric tons of ore plus waste moved per worker-shift; prorated administrative labor.

Mine operating cost estimates, based on 1984 dollars per metric ton of ore, range from about $3.50 to $11.56. These values reflect the total cost of moving waste and ore, which is then burdened solely to the ore tonnage. For comparing operating costs among operations, it is more valid to look at the costs on the basis of the total material moved (ore plus waste basis). When this is done, the producing surface gold mines in the continental United States basically split into two different classes of operations: (1) low-cost operations, which can move a ton of material for $1.06 to $1.54, and (2) high-cost operations with corresponding costs of $2.23 to $4.15. Table 35 summarizes the important characteristics that differ between the two classes. Several generalizations regarding these two classes can be made:

1. Those operations with high costs on a ton of ore plus waste moved basis are low-tonnage, 100-pct heap leach operations with mostly contract mining (60 pct) using smaller front-end loaders (FEL's) 3.8- to 5.3-m³ capacities and trucks (30- to 45-mt capacities). For this study, where an operation was contracting out its mining, the estimated operating costs had a 20-pct profit factored into the estimate, representing contractor profit.
2. The low-cost operations are high-tonnage operations, treating mostly milling ore (66 pct of the operations) with

Table 36.—Classification of producing surface operations by level of mine operating cost and grade of demonstrated resource

Class of operation	Number of operations[1]	Overall weighted-average grade of demonstrated resource, g/mt
Low-cost surface mines, milling ore	6	3.45
Low-cost surface mines, heap leach ore	5	1.18
High-cost surface mines, heap leach ore	5	2.21

[1]Does not include the 1 dredging operation in California. 1 operation with both millable and heap leaching ore is counted twice.

noncontract mining. They employ a combination of shovel-FEL excavation with truck haulage using large equipment (4.6- to 10.0-m^3 FEL's and 45- to 77-mt trucks).

3. Contract mining appears to be favored when the operation plans to heap-leach the ore and the reserve for mining is indicated to be less than 10 yr, or where climatic conditions limit the mining season to 9 months of the year or less.

Table 36 summarizes the overall gold grade of the demonstrated resources for the surface mining operations. As shown, the demonstrated resources have been classified into three categories: (1) low-cost surface mines excavating "milling" ore, (2) low-cost surface mines moving ore for heap leaching, and (3) high-cost surface mines moving ore for heap leaching. The weighted-average gold grade for each of these three categories represents the overall weighted-average grades for the entire demonstrated resource evaluated for all of the operations in that category. As expected, those operations mining ore for milling in a conventional mill have the highest overall grade at 3.45 g/mt. Of more interest is a comparison of the overall grades at the low-cost and high-cost heap leach operations. These grades are 1.18 and 2.21 g/mt, respectively. This difference of 1.03 g/mt is significant because it represents additional revenues of approximately $9.30/mt, assuming a gold recovery of 70 pct and a gold price of $400/tr oz.

Table 37 attempts to show *how* lower mine operating costs at high-tonnage surface mines compensate for a lower grade of material that has to be leached. As shown, the mining cost at the low-cost heap leach operations is nearly 54 pct less on a per-ton-of-material-moved basis, or about 57 pct less on a per-ton-of-ore basis. This allows material grading 67 pct less to be heap-leached at a total production cost (mining plus leaching) that is only 30 pct ($29/tr oz recoverable gold) higher.

Underground Mining

Underground mining in 1983 represented only about 15 to 20 pct of total U.S. gold production from primary ores. As of early 1984, the only significant underground gold mine in the continental United States is the Homestake Mine in South Dakota, which has been in continuous production for 108 yr. One other significant underground primary gold producer closed in late 1983. Two mines are currently under development: the Ropes Mine in Michigan and the Cannon Mine in Washington. Several other prospective underground primary gold deposits were in various stages of exploration and study as of 1984; however, it is felt that for the near term the Homestake Mine should continue to dominate gold production from underground deposits in the United States.

Several aspects of the Homestake mining operation are of interest. First, as of the early 1980's the lowest level of workings was about 2,450 m in vertical depth, or slightly over 1½ miles deep. Second, the increase in the price of gold since the early to mid-1970's has allowed the feed grade to be lowered significantly, which in turn has allowed the mine to increase its use of high-volume, low-cost mining methods such as blasthole open stoping and vertical crater retreat (VCR) stoping. For example, in 1981, 43 pct of the mine's ore output came from blasthole stoping and VCR stoping, and 57 pct came from higher cost, cut-and-fill mining. Third, as of the early 1980's, major exploration of the deposit below the 2,450-m level was being conducted. These three aspects basically define the characteristics and concerns of the mine as of the 1980's, which are the increasing depth of mining and the need for flexibility in mining methods appropriate to changing economic conditions and gold price levels.

Because of the few operations involved, operating costs at underground gold mines in the United States are not discussed in detail. In general, the costs are or should be similar to the underground mining costs being experienced at most of the Canadian mining operations.

Table 37.—Effect of lower mine operating costs on the ability to mine and process low-grade material at selected producing heap leach operations in the Western United States

	Low mine operating cost[1]		High mine operating cost[2]		Difference: low-cost relative to high-cost operations, pct
	Range	Average	Range	Average	
Mining cost per metric ton of ore plus waste	$1.41–$1.50	$1.46	$2.23–$4.15	$3.21	−54
Mining cost per metric ton of ore leached	$3.00–$3.52	[3]$3.26	$6.48–$9.54	[4]$7.57	−57
Grade of material leached ...... g/mt	1.03– 1.28	1.16	1.82– 5.00	3.52	−67
Recovery factor ...... pct	NAp	0.70	NAp	0.70	NAp
Recoverable gold per metric ton of ore leached ...... g	NAp	0.81	NAp	2.46	−67
Ore required to produce 1 tr oz recovered gold ...... mt	NAp	[5]38.4	NAp	[6]12.6	NAp
Mining cost per troy ounce of gold recovered	NAp	[7]$125	NAp	[8]$96	30

NAp Not applicable.
[1]Data for 2 100-pct heap leaching operations, costs as of Jan. 1984.
[2]Data for 3 100-pct heap leaching operations; costs as of Jan. 1984 include contract mining.
[3]Determined as follows: $1.46/mt ore plus waste multiplied by the average stripping ratio of 2.23 for the 2 properties included.
[4]Determined as follows: $3.21/mt ore plus waste multiplied by the average stripping ratio of 2.35 for the 3 properties included.
[5]Determined as follows: 31.1035 g/tr oz divided by 0.81 g/mt = 38.4 mt required to produce 1 tr oz gold.
[6]Determined as follows: 31.1035 g/tr oz divided by 2.46 g/mt = 12.6 mt required to produce 1 tr oz gold.
[7]Determined as follows: 38.4 mt multiplied by $3.26/mt ore leached = $125.
[8]Determined as follows: 12.6 mt multiolied bv $7.57/mt ore leached = $96.

Table 38.—Operational characteristics of producing gold mills in the continental United States, by type of milling method, circa 1983

	Number of operations	Annual ore capacity, 10^3 mt	Annual gold recovery, 10^3 tr oz	Mill feed grades, g/mt gold		Recoveries of gold, pct	
				Range	Weighted average	Range	Weighted average
Heap leaching	9	10,165	405	0.95 – 5.5	1.7	60 – 85	71.3
Vat leaching (conventional milling)	7	7,550	924	1.63 – 7.9	4.6	70 – 94	88.0
Bulk float-leach tails	1	50	13	NAp	8.6	NAp	92.0
Dredging (gravity separation)	1	6,400	22	NAp	.14	NAp	80.0
Total	18	24,165	1,364	NAp	NAp	NAp	NAp

NAp Not applicable.

Placer Mining

Because of limitations on the minimum size of the gold producing operations analyzed in this study, only two major placer operations, one producing and one in study as of 1984, were evaluated.

The producing operation began production in 1980. It is near Marysville, CA, and required the renovation of a dredge that had last operated in 1967. In renovation, the maximum excavation depth was increased to allow excavation from a depth of 42.7 m below the water level of the dredging pond. The operation also involves a large amount of overburden removal using FEL's and conveyor belts to increase the area available for dredging. The operation has been so successful that plans as of 1982 were to renovate a second dredge to operate in a nearby area.

The evaluated nonproducing placer operation would have an output capacity equivalent to that of a major producer and would be somewhat unique in concept. Initially, bulldozers and FEL's will scrape overburden into trap loaders feeding conveyor belts for transport to waste or reclamation areas. With increased mining depth, an advanced overburden removal system will be required to remove overburden on the extreme western edge of the mine.

Following the overburden removal stage, low-grade fluvials will be mined by bulldozers and processed in skid-mounted trommels and concentrating plants. The concentrating plants will be stationed in an interim processing water pond. As mining progresses, these concentrating plants will be positioned on benches.

In a third stage of mining, high-grade gravels will be excavated with a backhoe, a hydraulic breaker, a ripper mounted on a backhoe, and an FEL. When the lowest bench is formed it will be approximately 12.2 m above bedrock, and subsequent excavations from this bench will be below the water table. These excavations will fill with water to form a pond capable of floating a barge equipped to process the high-grade gravels. These three mining stages will be initiated at staggered intervals so that each is in advance of the other.

In the concentrating process, trommels will wash and size low-grade gravel to less than 9.525 mm; high-grade gravel will be sized to less than 19.05 mm. A desliming tank will separate the heavy metals from clay. Screens and pulsating jigs will produce a gold concentrate, which will flow to the amalgamation circuit. Amalgam (a mixture of mercury, gold, and black sand) will be retorted in an air-tight metal tank; retorted gold will then be melted in a furnace and formed into bullion.

When both these placer operations have attained their full capacity, as proposed circa 1982–83, they should account for about 100,000 tr oz combined annual production. However, based on the demonstrated resource analyzed in this study, the operations have mine lives extending only to 1992–95. The economics of these large placer operations appear to be favorable at the reported grades of the material being mined or planned for mining. Weighted-average grades range from 0.1 to 0.5 g/mt. Long-run production costs are estimated at $300/tr oz to $350/tr oz recovered gold. It must be remembered that placer operations this large are always high-profile operations in terms of environmental aspects. Thus, even though the economics of these operations appear favorable, a "boom" of similar developments should not be expected.

GOLD MILLING IN THE CONTINENTAL UNITED STATES

The 16 major gold producing operations in the continental United States as of 1983 included 8 operations that were using heap leaching to produce gold bullion, 6 that were using conventional crush-grind-vat leach methods to recover gold, 1 that was using a combination of heap leaching and conventional vat leaching, and 1 that was using a dredge and gravity methods for gold recovery. An additional operation of interest due to its beneficiation technique was one that was producing a bulk flotation concentrate product and then leaching the tails from flotation to produce dore bullion.

Table 38 summarizes the pertinent estimated operational data covering the four basic types of milling operations. The Carlin operation in Nevada, which utilizes a combination of heap leach and conventional milling, is accounted for in table 38 as one operation in each of two categories. The data in the table represent circa 1983 operational data and do not necessarily reflect expected or proposed changes to the capacities and milling methods that have been evaluated in this study when addressing the economics of these operations over their total productive lives.

The operation that was floating its ore and leaching the tailings closed down in late 1983 and has only an estimated 3-yr reserve remaining. This operation was not included in the cost analyses but is briefly discussed from a comparative technical perspective. The two predominant methods in use, heap leaching and conventional vat leaching, are discussed in detail.

Heap Leaching (Solution Mining)

Heap leaching of gold ores is a recent development in the U.S. gold mining industry. A correct term for this method would be "solution mining" of prepared ore dumps with cyanide solutions.

The method was developed to economically treat low-grade gold ores (primarily less than 3 g/mt) through much lower capital requirements and lower operating costs per ton of ore treated in the milling stage. It is a particularly good method when treating disseminated oxide ores of the type discovered in the 1960's and 1970's in the Western United States.

In most cases, the material to be leached is first delivered to a crusher. The crushed ore is then delivered by truck to specially prepared leach pads. A cyanide solution of appropriate strength and pH is then evenly distributed on the heap through sprinklers and allowed to percolate through. The gold particles dissolve in the cyanide solution, which is collected in sumps and pumped to the gold recovery plant. The gold is extracted from the solution by one of two methods, the carbon-in-pulp (CIP) method or the Merrill-Crowe deaeration-zinc dust precipitation method. In the first case, the gold in solution is adsorbed onto granules of carbon which are then stripped of the "loaded" gold by a hot NaOH solution. This solution is in turn fed to electrowinning cells where the gold deposits onto cathodes of steel wool. In the second method, the product is a zinc-dust precipitate, which is filtered. The cathodes (in CIP) or the precipitate (in Merrill-Crowe) are then melted in crucible furnaces along with fluxing materials such as borax, niter, and silica. The resultant product from the smelting is a dore bullion of precious metals grading anywhere from 35 pct gold and 55 pct silver to 96 pct gold and 3 pct silver. In practice, there are many variations to the "normal" description of heap leaching given above, and subsequent discussion will attempt to describe some of the variations being practiced as of 1983 in the United States.

The economics of a heap leaching operation are very dependent upon the gold recovery that is obtainable. Because the ore grades are so low (less than 1 g/mt leached in some cases) it is difficult to exercise effective grade control. Thus, heap leaching operations can experience grade variations from month to month or year to year of as much as 25 to 50 pct, and the operations have to have a built-in flexibility to be able to increase tonnage and reduce operating costs through economies of scale.

Location is also important for two reasons. First, one of the major advantages to the heap leaching method is the low capital cost required for the gold recovery operation. Thus, if the proposed mine is in a remote location with attendant high cost requirements for infrastructural investments, this capital cost advantage could be negated. Second, heap leaching works best in dry or arid and temperate to hot climates. Cold temperatures negatively affect normal heap leaching operations because the solubility of gold decreases greatly below 50° F and because the leaching solution could freeze. Wet climates, especially those prone to intense rain storms, pose a problem in that sudden deluge would rapidly dilute the leaching solution and could cause the collection ponds to overflow.

As to the mineralogy of the ore itself, one principle is of paramount importance: The best recovery of gold will be obtained where the most contact can be made by the leaching solution on the majority of those gold particles amenable to dissolution. In this regard, high clay contents in the ore are undesirable because clay causes uneven percolation of the leaching solution. High amounts of sulfide minerals in the ore are also undesirable because of preferential leaching of base metals such as copper, lead, and zinc and because some of the gold particles will be "locked-up" in sulfide minerals. Carbonaceous ores (ores containing a high amount of organic carbon) are difficult because the carbon particles in the ore preferentially absorb the gold before it can be recovered in the leach solution. Oxidized ores are favorable for heap leaching because the solubility of gold is improved by higher oxygen contents during the solution stage. In addition, oxide ores usually contain more gold particles in the "native" form, and base metals are not present in large amounts. Another favorable type of heap leaching ore is material where the gold mineralization is disseminated throughout the ore rather than clustered in specific zones because percolation will contact more of the gold particles. All of these mineralogic factors have a major effect on the overall recovery of gold in the heap leaching process.

As shown in table 38, nine major producing heap leaching operations were analyzed for this study. Five of the operations are located in Nevada; New Mexico, Colorado, Montana, and Idaho each have one major heap leaching operation included in the analysis. One of these operations, a small producer in Colorado, is an anomaly in attempting to categorize it as either a heap leach or a vat leach milling operation. This operation incorporates aspects of both methods in that its ore is placed into large vats enclosed in a building because of climatic conditions and then is subjected to an intense cyanide leach. Another of the nine heap leaching operations is also anomalous in comparison with the others in that this operation simply places run-of-mine ore (no crushing and no agglomeration) on the leach pad, builds berms around the top of the pad, and develops a pond of cyanide leach solution on top of the ore heap rather than using sprinklers. This operation also does not remove the leached ore from the pad at the end of the leaching cycle, choosing instead to construct a new pad for subsequent leaching.

It is estimated that the nine heap leach operations accounted for 405,000 tr oz of gold production in 1983, which represents nearly 30 pct of total primary gold production from the 16 major producers evaluated in this study. This 1983 production level is an eight-fold increase over the reported 1979 production from solution mining of gold ores, which was slightly more than 50,000 oz of gold. This eight-fold increase is easily explained when it is noted that seven of the nine operations have come on-line since late 1979.

The ore grades ranged from 0.95 to about 5.5 g/mt, with a straight average grade of 2.3 g/mt and a weighted-average grade of 1.7 g/mt of leached material. Estimated recoveries of gold at the nine heap leaching operations range from 60 to 85 pct with a straight average of 75 pct and a weighted-average recovery of 71 pct. The range of recoveries from 60 to 85 pct defines fairly well the two extremes to be expected in the heap leaching of predominately oxide ores.

It is difficult to summarize the nine major heap leaching operations in production in the United States during 1983. At least one major operational characteristic varies among the nine operations. The most common methods, along with the number of operations utilizing them, are listed in table 39.

Somewhat surprisingly, as of 1983, only four of the nine operations were agglomerating their crushed ore prior to placement into heaps. Agglomeration of the ore with water and binders, such as cement, "balls" the ore into particles of similar shape and size, allowing a more even distribu-

Table 39.—Number of U.S. heap leach operations utilizing various mining and processing methods

Crushing of ore prior to leaching	7
Agglomeration prior to placement into heaps	4
Distribution of solution with sprinklers	8
Extraction of gold using the carbon-in-pulp method	6
pH control with lime	7
Distribution of ore and building of heaps with trucks and bulldozers	7
Rehandling of leached material	8
Asphalt base for leach pads	6

tion of the percolating solution within the entire heap. It is especially recommended where the ore contains a fair amount of clay minerals or fines material since, in both cases, segregation due to placement will cause impervious layers to develop within the heap and the cyanide solution will be diverted along these impervious boundaries.

Not surprisingly, six of the operations were using the carbon-in-pulp method of extracting the gold from solution. The three operations that were using the conventional Merrill-Crowe system of extraction were all producing dore bullions which contained more silver than gold and have appreciable silver contents in the ore, in which case carbon methods are not preferred.

The majority of the operations control the pH level of the cyanide solution with lime rather than caustic soda ($NaOH$), and must distribute and build their heaps with trucks and bulldozers. The two anomalies regarding heap building are an operation that uses a traveling gantry for distribution onto the heap and an operation that does its heap leaching in large vats in an enclosed building where a front-end loader distributes the ore.

The most variable production aspects among the nine operations occur in four areas: (1) the leach cycle time, (2) the number and sizes of the leaching pads, (3) the configurations of the ore heaps, and (4) the number of months in a year that leaching is conducted. Leach cycles (including leaching and the removal and treatment of leached material) range from 4 days to 3 yr; the majority are in the 1- to 3-month range. The storage capacity of permanent leach pads ranged from 20,000 to 1.0 million mt of ore. The configurations of heaps range from "pyramidal" to "furrowed." In terms of the leaching season, six of the nine operations were limited to 7 to 9 months of the year, while three were conducting their leaching virtually year round. Of these three year-round operations, only two could do this because of natural climatic conditions; the third operation was heating its leach solution to allow full leaching for 9 months of the year and part-time leaching for the other 3 months. However, heating the cyanide solution causes appreciable loss of cyanide.

The estimated operating costs for the heap leaching stage at the nine operations range from \$2.39/mt to \$10.52/mt ore. These costs represent the costs incurred from the point of ore delivery to the crusher or to the heaps, depending upon the particular situation, and include the costs of rehandling the leached material at the end of the leaching cycle, which in some cases is done by the mining contractor. The two highest estimated operating costs of \$8.75 and \$10.52 reflect one operation with higher than normal labor costs and one operation with extremely high cyanide consumptions. Thus, the more normal range of heap leach operating costs, on a per ton of ore basis, is \$2.39 to \$7.37, a range that encompasses seven operations. This normal range, in turn, appears to split into two separate classes: a low-cost class in the range of \$2.39/mt to \$4.05/mt, and a high-cost class in the range of \$4.86/mt to \$7.37/mt. A comparison of various characteristics for these two classes is shown in table 40. The items listed are felt to be the major determinants of whether a particular heap leaching operation will be in the low-cost or high-cost class.

As shown, labor productivities average nearly 48 pct higher at the low-cost operations, which is mostly a reflection of the larger pad sizes. The low-cost leaching operations also show an advantage in the high proportion that do not have to crush and/or agglomerate their ore and that can operate year- round.

Table 40.—Labor productivity and operational characteristics for low-cost and high-cost heap leaching operations in the continental United States

	Low-cost heap leaching	High-cost heap leaching
Number of operations	3	4
Annual ore capacity:		
Range . . . 10^3 mt/yr	344–3,265	475–780
Average . . . 10^3 mt/yr	2,290	550
Pad capacities . . . 10^3 mt	250–1,000	20–136
Labor productivity[1] per worker-shift, mt:		
Range	80–92	42–68
Average	87	59
Percentage of operations using—		
Crushing	33	100
Agglomeration	0	75
Waste removal	67	100
Year-round operation	67	25

[1]Includes prorated administration labor

In the normal range of operating cost levels for heap leaching, the costs for direct and indirect labor constitute the largest single item, ranging from about 30 to 38 pct of the total for the low-cost class and 28 to 38 pct for the high-cost class, with both classes averaging about 33 pct. The miscellaneous cost category, including maintenance materials, insurance, miscellaneous supplies, and water, represents the second largest portion of the total operating cost, with the low-cost operations averaging 31 pct and the high-cost operations averaging 33 pct. Reagent costs are the third most important cost category, averaging about 18 pct at the low-cost operations and about 21 pct at the high-cost operations. Electricity costs and energy costs (gasoline, heating oil, and propane) constitute the smallest portion of total operating costs in both classes at 18 pct on average for the low-cost class and 13 pct on average for the high-cost class.

The following items deal with some generalizations concerning the costs of specific operations that are intended to give the reader a rough idea of the cost levels associated with these tasks. First, for operations of smaller capacity and in the high-cost class, crushing costs appear to range from about \$1.25/mt to \$2.20/mt ore. Rehandling of waste range from about \$0.35/mt to \$1.72/mt ore. Second, one gold operation reported a cost for constructing an asphalt-based leach pad of slightly more than \$15 per square meter in 1982. Third, in all cases, cyanide costs represent the first or second largest item in the costs for reagents, while costs for cement, lime, soda ash, carbon, and nitric acid vary among the top three individual reagent costs from operation to operation.

To summarize, heap leaching is a relatively new method of recovering gold and could be considered as still in the development stage because the operational characteristics make it an ideal method of experimentation. With low capital and operating costs, heap leaching has enabled gold ore of very low grade to become competitive with much higher grade gold deposits. The method, however, requires high efficiency in the mining and milling operations, along with a high degree of built-in flexibility to the operation. Also, at present gold prices, the method is limited to certain types of ores and is subject to infrastructural and climatic constraints. In addition, the gold grades of the material leached and recoveries experienced can be extremely variable, and much attention should be paid to initial metallurgical tests of the ore before proceeding with a heap leaching operation. A recent Bureau publication (*24*) discusses heap leaching technology, lists 118 leaching operations, gives details on 26 key operations, covers Federal and

Table 41.—Comparative economics of producing heap leach and conventional milling operations in the continental United States

	Entirely surface mining and heap leaching operations	Entirely surface mining and conventional milling operations
Number of operations	8	5
Total capital investment remaining[1]	7 operations less than $20 million; 5 operations less than $10 million.	3 operations greater than $60 million; 4 operations greater than $40 million.
Capital cost per troy ounce:		
Range	$26 to $126	$21 to $82.
Weighted average	$47	$46.
Total (mining plus processing) operating cost per troy ounce:		
Range	$117 to $401	$146 to $332.
Weighted average	$288	$247.
Total operating plus capital cost per troy ounce:		
Range	$152 to $527	$182 to $397.
Weighted average	$335	$214.
Break-even (0-pct DCFROR):		
Range	$173 to $538	$187 to $428.
Weighted average	$349	$268.
10-pct DCFROR:		
Range	$180 to $567	$210 to $489.
Weighted average	$360	$304.
Producing years from January 1984	4 operations, 3 to 6 yr; 3 operations, 7 to 10 yr; 1 operation, 51 yr.	1 operation, 6 yr; 4 operations, 12 to 15 yr.

[1]Unrecovered capital investment in mine and mill plant and equipment, infrastructure, and development remaining as of Jan. 1984 plus reinvestments through life of operation.

State requirements, and provides an extensive bibliography of over 160 references on gold and silver heap leaching.

In terms of annual output, the nine heap leaching operations evaluated in this study range from 6,500 to 83,000 tr oz of gold production, with an average annual output of 45,000 tr oz per operation. This compares with annual gold outputs ranging from 74,000 to nearly 200,000 tr oz/yr at the seven evaluated conventional vat mills with an average output of 132,000 tr oz/yr. In addition, the mine lives of the heap leaching operations tend to be somewhat less than those of conventional milling operations. Thus, probably at least three average heap leaching operations have to be developed in order to replace the annual gold production capacity at one average conventional milling operation in the United States.

Comparative Economics of Heap Leaching and Conventional Milling

The economics of heap leaching differ from those of conventional milling in four significant ways:

1. Total initial capital investments in plant and equipment, infrastructure, and development required to bring the operation into production are lower.
2. Total capital reinvestments over the mine life are lower.
3. The preproduction period required to bring the operation into production is shorter.
4. The payback period, due to significantly lower capital investments, is shorter.

Table 41 presents comparative data on eight producing surface operations employing 100 pct heap leaching and five producing surface operations employing 100 pct conventional milling. The most significant economic difference between the two is in required total capital investments over the mine life (the sum of items 1 and 2 above). Seven of the eight evaluated heap leach operations have total estimated capital investments, remaining as of January 1984, of less than $20 million, and five of the eight have total capital investments of less than $10 million. By contrast, four of the five conventional milling operations have total required capital investments exceeding $40 million, and three operations have total capital investments exceeding $60 million. The barrier to market entry, therefore, into gold production from heap leaching of surface material is much lower than for conventional milling operations. The relatively low total capital costs required for the development and operation of heap leaching deposits thus render them viable investment opportunities for small mining companies with low capitalization. This is the primary reason for the increase in the number of heap leaching operations that have come into production since 1979.

Conventional milling operations are generally larger in terms of annual output, require greater investments in facilities such as mill plant and equipment, and require higher capital reinvestments over the mine life. But since the grade of the ore is higher, total ore resources greater, and recoveries better, these conventional milling operations have essentially the same capital costs per ounce of recoverable gold. Total operating costs per ounce of recoverable gold (mining plus milling or leaching cost) significantly favor conventional milling, on a weighted-average basis. This is not only because of higher grade ore and higher milling recoveries but also because of higher annual production levels.

Break-even, long-term total production costs per ounce of recovered gold for the eight evaluated heap leach operations range from $173 to $538, with a weighted average of $349. Seven of the eight operations fall in a range from $173 to $425. The increase in gold prices in recent years and the development of the heap leaching process have served to broaden the market in terms of the sources of gold production in the Western United States. On average, the five conventional milling operations have lower total production costs than the heap leaching operations, thus demonstrating economies from larger scale production and higher grade ore as an offsetting factor to higher total capital investments.

As analyzed in this study, the heap leach operations, on average, have shorter mine lives than the conventional milling operations. Seven of the eight heap leaching operations have estimated remaining lives of less than 11 yr, and four operations have remaining lives of only 3 to 6 yr. By contrast, four of the five operations employing conventional milling have remaining productive lives of between 12 and 15 yr.

Vat Leaching Of Gold Ores

During 1983, eight of the major primary gold producing operations analyzed in this study were using conventional milling techniques (vat leaching) to treat at least some of their ore production. Conventional milling, or vat leaching, as defined for this study, is any mill that crushes and grinds its ore and performs cyanide leaching in agitation vats. Seven of the eight mills produce precious metal (dore) bullion by crushing, grinding, leaching, and gold extraction with various methods plus smelting. The remaining mill was producing a bulk flotation concentrate containing most of the gold and silver and then leaching the tailings from flotation to produce a small amount of dore bullion; this operation has since closed down. In terms of geographic location, four of the eight mills are located in Nevada with one mill each located in Utah, Montana, South Dakota, and Washington. The oldest of the mills was constructed in 1937, another basically dates from 1952–53 when a major renovation was made, one dates from the mid-1960's, and one was originally constructed as a copper mill in the late 1960's and then converted to a primary gold mill in 1978–79. The remaining four mills are all relatively new, two being commissioned in 1981 and two brought into production in 1983.

Table 42.—Comparative characteristics of major vat leaching mills in the continental United States, circa 1983

	Mills less than 5 yr old	Mills more than 10 yr old	Total or average
Number of mills	5	2	7
Combined annual ore capacity ....10^3 mt.	5.17	2.38	7.55
Combined annual gold production capacity ....10^3 tr oz.	518	419	937
Weighted-average feed grade ....g/mt.	3.7	6.1	4.4
Weighted-average mill recovery ....pct.	84	93	87

If the copper mill that was converted to primary gold milling is included as a "new" mill, then the five mills brought on-line in 1979–83 represent sufficient capacity as of late 1983 to treat slightly more than 5.2 million mt/yr ore to produce nearly 520,000 tr oz/yr gold. The three older mills, as of late 1983, had the capacity to treat about 2.4 million mt/yr ore to produce nearly 420,000 tr oz gold. Combined, the eight major mills were probably producing about 940,000 tr oz gold in 1983, or more than two-thirds of total U.S. primary gold production.

Since the mill in Washington State that was producing a bulk flotation concentrate and dore bullion was shut down late in 1983 and has a limited (2- to 3-yr) reserve of ore, the following discussion will concentrate on the seven major vat leaching mills currently in operation.

Table 42 summarizes the operational characteristics of the two groups of conventional gold mills: those less than 5 yr old and those more than 10 yr old. The five newer mills have productive capacities ranging from 445,000 to 1.7 million mt/yr ore to produce between 73,000 and 196,000 tr oz/yr gold. The two older mills range from 700,000 to 1.7 million mt/yr ore milling capacity to produce from 128,000 to 279,000 tr oz/yr gold.

Of particular interest in table 42 are the lower feed grades and lower recoveries at the newer mills compared to the older mills. The lower feed grades at the five newer mills reflect the increase in the price of gold since the mid-1970's, which enabled lower grade deposits to be brought into production. Even though the two older mills were treating ore in 1983 that graded 50 pct higher than the newer mills' ore, they have also lowered their feed grades in response to the gold price increase. For example, in 1974 these two mills produced about 530,000 tr oz gold from 2.2 million mt ore, whereas in 1983 the two mills produced about 420,000 tr oz gold from 2.4 million mt ore, a decrease of 29 pct in the weighted-average feed grade and a 21-pct decrease in overall gold production. Yet, using average gold prices of $160/tr oz for 1974 and $425/tr oz for 1983, the indicated 1983 revenue from these two mills' production is 214 pct higher than 1974's estimated revenue. Even if the estimated revenues for 1974 and 1983 are compared on a constant-dollar basis, the estimated revenue for 1983 is still 15 pct higher than 1974's estimated revenue despite a 20- to 30-pct decrease in feed grades and production.

As in Canada and Australia, it is difficult to categorize the major vat leaching gold mills in the continental United States because the ores all have slightly different characteristics. Table 43 shows the variations in practices

Table 43.—Variations of major circuit practices at vat leaching gold mills in the continental United States, early 1980's

Major circuit	Method or practice	Number of mills using method or practice
Ore blending	Carbonaceous with noncarbonaceous ores	1
Comminution	Single-stage crushing; grind with SAG mill and ball mill	2
	2- or 3-stage crushing; grind with rod and/or ball mill	5
Coarse free gold recovery	Launder traps in grinding circuit	1
	Jigs and tables with grinding circuit	1
Special treatments	Separation into major sand and slimes fractions	1
	Oxidation of pyrrhotite with air	1
	Oxidation of carbonaceous ore with chlorine gas	2
Extraction of gold from cyanide solution	Carbon-in-leach (CIL) with electrowinning onto steel wool	1
	Carbon-in-pulp (CIP) with electrowinning onto steel wool	4
	Carbon-in-pulp (CIP) with zinc dust precipitation	1
	Merrill-Crowe deaeration-clarification with zinc dust precipitation	2
Carbon reactivation	In gas-fired kilns	6
	In kilns or with nitric acid wash	1
Special byproducts	Mercury production by retorting steel wool or filter cake	3

at the seven major vat leaching gold mills as of the early 1980's. The categorizations shown point out six major aspects of interest.

First, only two of the seven mills include some provision for recovery of coarse, free gold in their circuits. One mill recovers slightly more than 20 pct of its total recoverable gold with the use of launder gold traps in its grinding circuit, while the other mill recovers from 10 to 20 pct of its gold by using jigs and tables to treat the cyclone underflow from the ball milling circuit. In total, only about 7 pct of the annual gold recovered at the seven milling operations represents coarse, free gold recoverable by gravity methods.

Second, carbon methods for extracting gold from the cyanide leach solution are used in six of the eight separate extraction circuits involved. The two extraction circuits that use the older Merrill-Crowe deaeration-clarification method are mills that are more than 10 yr old; these mills have obviously found no reason to change the original extraction method at their older circuits. However, 100 pct of the extraction circuits constructed at major vat leaching mills in the continental United States within the last 10 to 11 yr have been carbon method circuits.

Third, all six circuits using carbon methods for extracting gold from cyanide solution reactivate the stripped carbon particles in gas-fired or indirectly fired kilns. At one operation, the stripped carbon is sometimes reactivated by using a nitric acid wash.

Fourth, mercury is produced at three of the seven milling operations. The mercury is present in the steel wool cathodes from electrowinning or in the filter cake from zinc dust precipitation. At those operations producing mercury for sale, the cathodes or filter cake are smelted and the vaporized mercury is condensed to liquid form for sale in flasks. The residue from this first smelt is then resmelted in the presence of fluxes such as niter, borax, and silica to produce the final dore bullion product containing the precious metals. The amount of mercury produced is not large, and revenues from mercury are miniscule compared to those from gold and silver.* The three operations that produce mercury as a byproduct are the same three that treat carbonaceous ore as a portion of the total ore feed.

Fifth, one of the seven vat leaching operations makes a major split of its ground ore into a sand fraction (about 60 pct of the total tonnage treated) and a slimes fraction (about 40 pct of the total tonnage treated). The sand fraction is leached in vats with gold extraction by the Merrill-Crowe-zinc dust precipitation method, while the slimes fraction is pumped 4.8 km to a vat leaching plant which uses carbon-in-pulp absorption, stripping with a hot caustic solution, and electrowinning of the gold onto steel wool.

Sixth, and possibly of most interest, is that three of the seven operations must contend with carbonaceous feed of a refractory nature. Material referred to as "refractory" is not rigorously defined; basically it is any material with a high organic carbon content in proximity to the gold particles and/or a fair amount of the gold "locked up" in pyrite that results in very low gold recoveries when treating the ore with normal cyanide leaching techniques. To obtain reasonable (over 70 to 80 pct) gold recoveries with this type of ore, it is necessary that the ore be oxidized prior to the cyanide leach.

*Only two of the three operations have reported their level of mercury production. The values given approximated 50 and 250 flasks of mercury per year.

Of the six major points discussed above, it is appropriate that two of these major points should be expanded upon in separate discussions. These two items, the predominant use of carbon extraction methods and the handling and treatment of carbonaceous (refractory) gold ores, are the two most important developments in the vat leaching of gold ores in the United States since the late 1960's. Interestingly, both of these developments were heavily dependent upon joint research efforts of major U.S. gold mining companies and Bureau of Mines metallurgical research facilities.

Extraction of Gold With Activated Carbon

The first major attempts to utilize the ability of activated charcoal or carbon to absorb complex metal ions in the processing of gold ores occurred in the 1940's and 1950's. The Golden Cycle mill in Cripple Creek, CO, the Getchell mine near Golconda, NV, and the Idria Mine in the country of Honduras are cited as three of the earliest plants to utilize the carbon-in-pulp process. These earlier plants were recovering the gold-loaded carbon from the slurry by screening or flotation and then recovering the gold from the carbon by burning the carbon or sending the gold-loaded carbon to a smelter. Unfortunately, the fixed gold price of the 1950's and 1960's caused these three operations to close, and the CIP process was temporarily forgotten (*25*, p. 95).

Three developments in the late 1960's and early 1970's caused a resurgence of interest in the CIP method. First, the price of gold was allowed to find its own level, raising the possibility of higher prices in the future. Second, the Bureau of Mines Research Center at Reno, NV, developed a hydrometallurgical method to strip the gold from the carbon particles using a hot, caustic-cyanide washing solution under elevated pressures. The resulting solution containing the stripped gold was then sent to a specially developed electrolytic cell (the Zadra cell) for electrowinning the gold onto cathodes of steel wool. Third, the largest gold producer in the United States, the Homestake operation in South Dakota, was attempting to find a solution to increased labor costs at its slimes leaching plant, where the requirement to filter-press 1,800 mt/d of slimes was becoming burdensome (*25*, p. 95).

As a result, Homestake Mining Co. and the Bureau of Mines Reno Research Center conducted a joint pilot plant operation at Lead, SD, in 1971. The results were favorable, and a full-scale 2,177-mt/d CIP plant was constructed in 1972–73. This plant was the first major CIP plant constructed in the United States to use the new caustic solution washing-electrowinning procedures. A second CIP plant was constructed by Homestake Mining Co. at Creede, CO, in 1975–76, and a third major plant came on-stream in 1979. This plant was at Duval Corp.'s Battle Mountain operation, where a copper flotation mill was converted to a CIP gold ore processing plant. In 1980–83, four other major vat leaching plants using carbon methods to extract the gold came on-stream.

As practiced currently in the CIP method, carefully sized particles of activated carbon are contacted with the pulp (leached ore plus cyanide solution) from the vat leaching stage. This contact takes place in stages in a series of tanks. The barren activated carbon is introduced to the last tank in the series and is advanced countercurrently to the pulp flow. Thus, the most "unused" carbon is contacted with the pulp that should have the least amount of gold available for absorption onto the activated carbon.

The gold-loaded carbon particles, suspended in a slurry, are then screened from the slurry and washed in a hot caustic-cyanide solution, usually under elevated pressures, to extract the gold from the carbon particles. The gold in the wash solution can be recovered either by electrowinning onto steel wool cathodes or by precipitation with zinc dust. The stripped carbon can be reused in the process after reactivation. This is usually accomplished by heating the spent carbon in a kiln, but washing the spent carbon with nitric acid will also reactivate it.

The above is a generalized description of the CIP method. Needless to say, there are technical variations in each plant in operation.

A second, more recent, carbon method is called the carbon-in-leach (CIL) method. In this method, the carbon particles are contacted with the pulp in the vat leaching stage itself, rather than after the leaching stage. This method is usually employed when the ore to be fed to the leaching stage contains a fair amount of organic carbon; the idea is to mitigate the deleterious effects on gold recovery caused by organic carbon in the ore. This is accomplished by introducing the activated carbon into the leaching stage where the deleterious effects occur.

As shown in table 43, of the six "gold extraction with carbon" circuits at major vat leaching mills in the continental United States, five use the CIP method and one uses the CIL method. Also, five of the six circuits use electrowinning onto steel wool cathodes, while one circuit uses zinc dust precipitation of the gold in the caustic-cyanide solution. Also, as noted previously, all six of the circuits reactivate the stripped carbon by heating it in kilns, with one of the circuits sometimes using a nitric acid wash.

The advantages and disadvantages of carbon methods of extraction versus the conventional Merrill-Crowe deaeration-clarification and zinc dust precipitation method of extraction are still being debated and involve many technical questions beyond the scope of this analysis. Original claims were that both capital costs for equipment in the carbon extraction circuits and operating costs are lower, mostly owing to lower labor requirements for the extraction circuit. In cases where all of the other factors contributing to overall capital costs and overall operating costs are equal, these claims will be true. The predominance of the use of carbon methods in the United States appears to be due to three major factors:

1. Labor requirements and maintenance and/or replacement costs are lower with carbon methods. This is in keeping with the stress placed on efficiency at all of the newer U.S. gold milling operations.
2. New mill circuits (constructed within the last 10 yr) are predominant in the United States.
3. The technology of carbon methods is probably most advanced in the United States.

Carbonaceous Gold Ores

Carbonaceous ores, those containing a high amount of organic carbon, are fairly common in the Southwestern United States. Because the organic carbon particles in this type of ore will adsorb gold that is present in the cyanide solution ("preg robbing"), recoveries of gold are very poor without some type of treatment to destroy as much of the organic carbon as possible before the cyanide leaching stage. There are no hard-and-fast rules as to the effect that the organic carbon content in a particular ore will have on the overall gold recovery without special treatment.[8] However, the general relationship is probably close to the experiences of the Carlin operation in Nevada, which was recovering only slightly more than 34 pct of the gold when milling its carbonaceous ore without special treatment versus as much as 83 pct of the gold when using an oxidation with chlorine gas treatment on the same type of ore (*26*, pp. 103–104).

Three of the seven vat leaching mills analyzed in this study have had to contend with carbonaceous ores. Two of the three operations have developed the preoxidation-chlorinoxidation method (also referred to as the "double-oxidation" method) of treating carbonaceous ores. The third operation, which is much lower grade than the other two, decided that oxidation of its carbonaceous ore was too costly and chose instead to blend the carbonaceous ore with its regular noncarbonaceous ore in a ratio of about 1:9, thereby attempting to control the effect of the carbonaceous ore on lower gold recovery. As a result of this decision this operation has the lowest overall gold recovery of the seven mills analyzed, with 70 pct being considered as good as can be expected with that particular blend of the two ore types.

The chloric oxidation method of treating carbonaceous ores was initially investigated beginning in 1967 with a joint research program between the Carlin Gold Mining Co. and the U.S. Bureau of Mines Metallurgical Research Center at Reno, NV. After extensive bench-scale testing, a pilot plant was constructed in 1969 to test the use of either chlorine or sodium hypochlorite as the oxidizing agent (*26*). The chlorine gas method was selected because generating sodium hypochlorite by electrolysis of the pulp involved high capital costs which were not justified by the size of the carbonaceous reserve involved. The chlorine oxidation circuit began treating ore on a fairly large scale at Carlin in 1971–72. In 1977, a preoxidation with air stage was added prior to the chlorine oxidation stage to oxidize some of the pyrite and pyrrhotite prior to the main oxidation stage. The second U.S. mill to utilize chlorine oxidation was constructed during 1979–81 and basically uses the same methodology as at Carlin.

At one of the two operations that treat carbonaceous ore by oxidation, 20 pct of the total annual ore milling capacity represents carbonaceous ore; at the other mill, fully 50 pct of the total annual ore capacity is for carbonaceous ore. Recoveries being experienced in the 1980's ranged from 83 to 87 pct of the gold in the carbonaceous ore at the two operations using the preoxidation-chlorine oxidation method.

A brief description of the process follows. First, when treating carbonaceous ore, the two basic types of ore, carbonaceous and noncarbonaceous, are handled separately in the crushing and grinding stage. The ground carbonaceous ore is slurried, and the pulp is heated using steam to 100° F at one operation and to 180 ° F at the other. The heated pulp is then sent to agitation tanks, where air is mixed with the slurry to oxidize as much of the pyrite, pyrrhotite, and other sulfide minerals as possible prior to the chlorine oxidation stage. The preoxidized pulp is then sent to another series of agitation tanks, where chlorine gas and air are introduced to oxidize the remaining sulfides and the organic carbon particles.

The method is expensive. For example, this study estimates that the "double-oxidation" method using

[8]Work by the U.S. Bureau of Mines and the U.S. Geological Survey as of the early 1970's had classified ores containing 0.25 to 0.8 pct organic carbon as carbonaceous ore and those containing 0.06 to 0.25 pct organic carbon as noncarbonaceous. However, as noted by Guay and Peterson (*26*, p. 103) the organic carbon assay was never found to be a highly useful tool in the metallurgical development work at the Carlin, NV, mill.

chlorine adds from $5.30/mt to $6.50/mt ore milled to the normal operating costs expected for straightforward cyanidation vat leaching, with the additional costs representing mostly chlorine consumption (13.6 to 22.7 kg/mt of ore milled) and steam generation for heating. Thus, it is not surprising that the two operations using the double-oxidation method with chlorine gas also are the two highest grade operations of the seven vat leaching mills studied, with average feed grades of about 6.5 g/mt to nearly 8.0 g/mt. A rough measure of the effect that this additional operating cost can have is that with a carbonaceous ore grading 6 g/mt, the added operating cost of $6/mt ore would represent an additional cost of $37/tr oz recovered gold, assuming an 85-pct recovery of gold with the process.

As summarized in table 42, the total combined annual ore capacity for the two vat leaching operations constructed prior to 1974 is 2.38 million mt/yr ore to produce 420,000 tr oz/yr gold. Individual feed rates as of the early 1980's for the two operations were 700,000 and 1.7 million mt/yr with feed grades of 5.5 and 6.3 g/mt, respectively, or 6.1 g/mt on a weighted-average basis. Total mill recoveries averaged 90 and 94 pct, respectively (93 pct on a weighted-average basis). In comparison, the total combined ore capacity for the five newer mills constructed since 1978 is 5.17 million mt/yr ore to produce about 518,000 tr oz/yr gold. Individual ore capacities at these newer mills range from 445,000 to 1.7 million mt/yr and average 1.04 million mt/yr. Individual outputs of gold at the newer mills range from 74,000 to 196,000 tr oz/yr gold for an average output of 104,000 tr oz/yr gold. Feed grades at the newer mills range from 1.6 to 7.9 g/mt with a weighted-average feed grade of only 3.7 g/mt, nearly 35 pct lower than the comparable value for the two older mills. Similarly, overall gold recoveries at the newer mills range from 70 to 90 pct with a weighted average of 84 pct, nearly 9 pct lower than the comparable value for the two older mills. The lower weighted-average gold recoveries at the newer mills reflect two factors. First, overall recovery of gold decreases as lower grade ores are processed, especially ores below 2.5 g/mt. Second, one of the five newer mills is processing a certain amount of unoxidized carbonaceous ore.

All seven of the vat leaching operations produce dore bullion as the final product. The dore bullions range in grade from 47 to 96 pct gold and have gold-silver ratios ranging from about 1:1 to as high as 48:1.

The estimated mill operating costs at the seven vat leaching operations range from $9.44/mt to $21.82/mt ore feed. This cost range includes appropriate weightings for those operations treating certain percentages of noncarbonaceous and carbonaceous ores. The estimated cost range for vat leaching of noncarbonaceous (normal) ores ranges from $9.44/mt to $17.76/mt ore feed. The requirement to utilize double oxidation with chlorine gas to treat carbonaceous ores is estimated to add $5.30/mt to $6.50/mt to the normal vat leaching operating cost, reflecting additional costs for chlorine and steam generation.

Indicated levels of productivity, including administrative labor at the older mills, range from 15 to 20 mt ore milled per worker-shift with an average of 17.5 mt. Productivity at the newer mills is more than double ranging from 26 to 75 mt ore milled per worker-shift, and averaging 37 mt.

Despite the reasonably high efficiencies at the vat leaching operations treating gold ores, the cost of direct and indirect labor, as a percentage, represents the single most important component of the overall mill operating cost, ranging from about 27 pct to over 50 pct with an average of 34 pct for all seven milling operations. At the newer mills, the second largest cost item, as estimated in this study, is the miscellaneous costs (all costs except direct and indirect labor cost, reagent costs, and energy costs), which have a wide range as a percentage of the total cost, generally from 16 to 46 pct with an average of 33.5 pct for the five newer mills. At the older mills, the miscellaneous cost items represent the third most important cost element, averaging 17.5 pct of the total cost. The estimated costs for reagents, expressed as a percentage of the total milling cost, are fairly consistent with a range from 15 to 26 pct of the total cost and an average of 22 pct for all seven operations. The costs for electrical energy and energy in the form of steam, propane, and fuel oil constitute the smallest individual major cost component at the vat leaching operations. As a percentage of the total operating cost, energy costs range from 5 to 27 pct with an average of 15 pct.

Refining and Transportation

It is estimated that as of 1981, total gold refining capacity in the continental United States was about 6.0 million tr oz/yr. This total represents capacity for refining dore bullion, anode slimes from copper electrowinning, copper-lead-zinc concentrates, and scrap and other residues. In 1981, copper-lead-zinc concentrates, anode slimes from copper refining, and other residues were being processed at eight facilities with a total production capacity of about 2.0 million tr oz/yr refined gold. Scrap and residue were being refined at 22 small facilities having a total production capacity in 1981 of about 800,000 tr oz/yr. Only three facilities—Englehard Minerals' refinery at Newark, NJ, Handy and Harman's refinery at Attleboro, MA, and Homestake Mining's refinery at Lead, SD—were accepting the main product of primary gold mining operations (dore bullion) along with scrap and residue. The three refineries accepting dore had a combined estimated production capacity of slightly more than 3.6 million tr oz/yr refined gold, with most of the capacity being at Engelhard's refinery. In 1981, the primary producers of gold in the Western United States were probably shipping about 900,000 to 1.0 million tr oz/yr dore bullion by air to these Eastern U.S. refineries.

Since 1981, two important developments have occurred in the geographical location of the refineries accepting dore bullion. First, Johnson Matthey Investments, Inc. of London, England, began construction of a major precious metals refinery in a suburb of Salt Lake City, UT. The $10 million facility was planned to have an initial production capacity of 1.5 million tr oz/yr refined gold and 5.0 million tr oz/yr refined silver with the design enabling the doubling of production capacity with minor changes. The refinery was dedicated on April 22, 1983. The second development occurred 1 yr later on April 5, 1984, when Englehard Minerals announced that it would close its refinery in Newark, NJ (*27*). The relationship between these two developments is not entirely clear, although the shift makes geographic sense with the increase of primary gold production in the Western United States.

The initial production capacity of 1.5 million tr oz/yr refined gold at the new Johnson-Mathey refinery is more than sufficient to handle the output from the *primary* gold operations evaluated in this study. For example, if the output of gold from the Homestake, SD, operation and the gold production from the small operation that closed in late 1983 are not considered, the 15 remaining major surface gold producers would account for about 1.05 million tr oz gold production in 1983. Thus, with the capability of easily doubling production at the Salt Lake City refinery, there will be sufficient refinery capacity to easily handle an additional 1.0 million tr oz annual *primary* gold production, should such a development occur between now and 1990. However, a large gold price increase could result in a large increase in recycled scrap material, which could swamp the refineries, as happened in 1980.

CANADA

HISTORICAL PERSPECTIVE

It is estimated that approximately 215 million tr oz gold were produced in Canada during the period 1858 through 1983. Canada has been the second-ranked market economy producer (behind South Africa) and the third-ranked world producer (behind South Africa and the Soviet Union) since overtaking the United States in 1930. Provided that the gold price remains about $400/tr oz, Canada should maintain this ranking into the 21st century, although some projections assert that Brazil may take over the third-ranked position by 1990.

Table 44 summarizes the major historical production developments of the Canadian gold mining industry. Except during 1974–81, Canada has produced over 2 million tr oz/yr gold since 1930. Fully 88 pct of total gold production from Canada has occurred since 1930. Major, sustainable levels of gold production were only attained with the development of the lode gold deposits in Ontario during 1909–25.

Figure 23 summarizes the Provincial distribution of gold production for selected years through 1983. As shown, gold production in the early years of this century was dominated by placer operations in British Columbia and Yukon Territory, whereas production from Quebec, Ontario, and the Northwest Territories was negligible. By 1933, these short-lived placer operations were replaced in importance by production from underground operations in Ontario and Quebec, which accounted for 85 pct of total production. Gold production since the 1960's has been dominated by Quebec, Ontario, the Northwest Territories, and British Columbia, which collectively accounted for 93 pct of total production in 1983.

RECENT PERSPECTIVE: 1968–83

Figure 24 depicts total mine production of gold in Canada for 1968–83, a period when the average annual gold price increased tenfold from $40/tr oz to $425/tr oz. The period just prior to 1968 had recorded a 34-pct production decrease from 4.629 million tr oz in 1960 to 3.062 million tr oz in 1967 (*20*). This decline is directly attributable to steadily increasing costs of production in the face of a fixed gold price. By 1970–71, when the United States lifted the gold backing for the dollar, production had further declined to slightly above 2.0 million tr oz/yr (*20*), the lowest level of production since 1930. The freeing of the gold price in 1970–71 did not halt the decline in Canadian production, which fell into a narrow range of 1.628 to 1.735 million tr oz/yr for a 9-yr period between 1973 and 1981 (*20*). Because the majority of Canadian gold production was from vein-type lode deposits during this period, it is most likely that the additional 20-pct decrease from the 1970–71 period to the 1973–81 period was caused more by a lowering of the mill feed grade at the surviving operations than by the actual closure of gold operations.

A major turnaround in gold production has occurred since 1981, with production in 1983 being 36 pct higher than in 1981. However, putting this increase into perspective, the 1983 level of production at 2.27 million tr oz (*20*) is basically the same as 1970 production and still about 400,000 tr oz less than production in 1968. It is estimated that the currently developing mines of the Hemlo District will add around 676,000 tr oz of annual output by 1989. Yet even with this addition, the projected output for 1989 will only be at levels prevalent in the 1960's and still far below the historical highs.

Table 44.—Historical summary of the Canadian gold mining industry

Year or Period	Occurrence or development
1823	Placer gold discovered on the Chaudiere River in Quebec Province.
1846	Silver veins reported in the vicinity of Thunder Bay, Lake Superior Region.
1852	Free gold discovered in quartz at Mitchell Harbour, Queen Charlotte Island. Causes the first auriferous quartz "rush" in British Columbia.
1857–65	Formal introduction of Canadian decimal currency occurs in 1858. First official annual gold production values are released for 1858, which totals 34,104 tr oz, all from British Columbia. Many placer gold discoveries occur in several Provinces during 1858–66.
1866	First discovery of gold in Canadian Precambrian shield near Madoc, Ontario.
1869	Gold discovered in the Yukon River.
1894-1900	Annual gold production increases substantially from 54,600 tr oz in 1894 to 1.3 million tr oz in 1900. Of the increase, 1.2 million tr oz (96 pct) comes from British Columbia and the Yukon Territory as a result of the discovery of placer gold at Klondike, Yukon Territory, in 1896.
1906	Annual gold production reaches a low of 406,000 tr oz as a result of a drastic decline in production from the Yukon placers.
1909	Dome, McIntyre-Porcupine, and Hollinger Claims are staked in the Porcupine District of Ontario.
1911–17	Teck-Hughes, Wright-Hargreaves, and Lake Shore Claims are staked in the Kirkland Lake District of Ontario.
1922	Annual production reaches 1.2 million tr oz, passing the 1.0-million-tr-oz mark for the first time since 1902. Ontario accounts for 1.0 million tr oz, or 83 pct, of the total.
1925	First discovery of lode gold in the Red Lake District of Ontario.
1930	Canada's annual production of gold surpasses U.S. production for the first time and passes the 2.0-million-tr-oz/yr level for the first time.
1935	Annual production passes the 3.0-million-tr-oz/yr level for the first time; Ontario accounts for 2/3 of the total.
1936	First cyanide mill in Canada is constructed in Nova Scotia.
1937–41	Annual production reaches 4.1 million tr oz in 1937 and soars to 5.3 million tr oz in 1941.
1942–45	Gold production drops 53 pct from the 1941 level to about 2.5 million tr oz in 1945.
1951–62	Annual gold production ranges from 4.1 million tr oz/yr to 4.6 million tr oz/yr, demonstrating fairly good stability.
1963–67	In 1963, Canadian gold production falls below the 4.0-million-tr-oz/yr level for the first time since 1937.
1968–83	Annual production continues to show a decline from 2.7 million tr/oz in 1968 to a low of 1.6 million tr/oz in 1980. First results from drilling in the Hemlo District, Ontario, announced in 1981. Annual production rebounds from 1980 low to 2.3 million tr oz in 1983.

Sources: References 20 and 28.

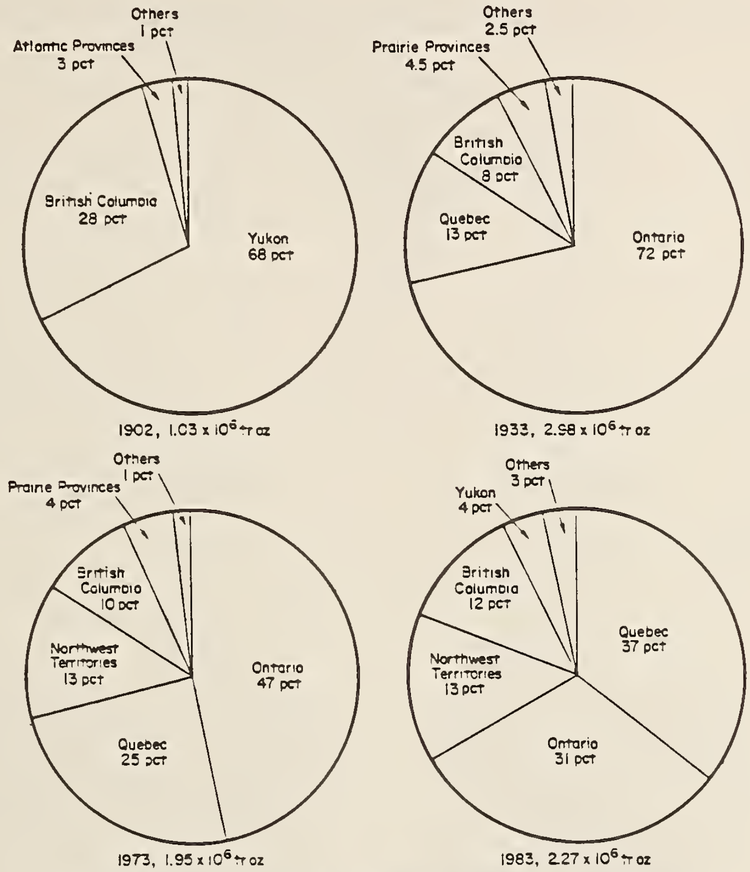

Figure 23.—Provincial distribution of Canadian gold production in selected years (pct and 10^6 tr oz).

Figure 24.—Total mine production of gold in Canada, 1968–83.

Figure 25.—Mine production of gold in Canada by type of deposit for selected years.

PRODUCTION BY DEPOSIT TYPE

Figure 25 presents Canadian gold mine production for selected years broken down by deposit type (*29*, p. 57; *30*, p. 62). As shown, 82 pct of total mine production in 1965 was accounted for by "auriferous quartz" or lode-type deposits. Base metal mines, producing gold as a byproduct of copper, lead, or zinc production, accounted for 17 pct, and placer deposits represented the remaining 1 pct. By 1980, production from lode-type deposits had declined by almost 2.0 million tr oz and represented only 60 pct of total production. Production from base metal mines had also fallen but by only approximately 50,000 tr oz and represented 34 pct of total production. Production from placer deposits had risen by around 50,000 tr oz and represented 6 pct of total production in 1980. By 1983, production from lode-type deposits had increased by 730,000 tr oz and accounted for 75 pct of total production. Byproduct gold production from base metal mines had fallen by 1.0 million tr oz, while placer production had increased slightly.

A comparison of total Canadian production with production from lode-type deposits demonstrates that the level of total production is extremely dependent upon the output from lode-type deposits. For example, 94 pct of the 1.3-million-tr-oz decline in total production from 1965 to 1980 was due to declines in output from the lode-type deposits. Likewise, the 647,000-tr-oz increase in total production from 1980 to 1983 was due to increased output from lode-type deposits, which increased production enough to both offset the declines in output from base metal mines and add to overall annual production. The following sections detail the geographical distribution of the three deposit types and discuss the number of mines producing from each deposit type by region.

Table 45.—Gold production from Canadian lode-type deposits, 1973 and 1981, by Province

Province	Number of operations		Percent of total lode production	
	1973	1981	1973	1981
Ontario	12	11	59.5	46.0
Quebec	6	10	23.0	37.5
Northwest Territories	4	6	17.5	13.5
British Columbia	0	3	.0	3.0
Total	22	30	100.0	100.0

Sources: References 31 and 32.

Lode-Type Deposits

Table 45 summarizes the provincial and operational aspects of lode deposit production of gold for 1973 and 1981, which are believed to exemplify the changes that have taken place in the Canadian gold mining industry. In 1973 there were 22 primary lode gold mines (owned or operated by 17 companies) producing 1.4 million tr oz/yr gold. By 1981, there were 30 primary lode gold mines (owned or operated by 25 companies) producing 1.1 million tr oz/yr. In both years, over 80 pct of lode gold production originated in Ontario and Quebec.

Three of the mines producing in 1973 had closed by 1981, while 11 new mines had come on-stream—6 in Quebec, 2 in the Northwest Territories, and 3 in British Columbia.

Table 46.—Byproduct gold production from Canadian base metal operations, 1973 and 1981, by Province or Territory, number and type of operation

Province or territory	1973		1981	
	Gold production, pct	Number and type of operation	Gold production pct	Number and type of operation
British Columbia	35	1 Fe-Cu, 1 Ag, 1 Pb-Zn-Cu, 10 Cu.	48.0	1 Ag, 1 Fe-Cu, 1 Ag-Cu, 2 Pb-Zn-Cu, 9 Cu.
Quebec	29	6 Pb-Zn-Cu, 6 Cu.	22.5	4 Pb-Zn-Cu, 4 Cu.
Ontario	15	3 Pb-Zn-Cu, 2 Ni-Cu, 2 Cu.	7.0	1 Pb-Zn-Cu, 2 Ni-Cu.
Manitoba and Saskatchewan	14	4 Pb-Zn-Cu, 1 Cu.	13.0	4 Pb-Zn-Cu, 1 Cu.
Yukon Territory	3	1 Pb-Zn, 1 Cu.	6.0	1 Pb-Zn, 1 Cu.
Newfoundland	3	1 Pb-Zn-Cu, 1 Cu.	2.0	1 Pb-Zn-Cu, 1 Cu.
New Brunswick	1	1 Pb-Zn-Cu	1.5	1 Pb-Zn-Cu
Total operations	100	42 NAp	100	35 NAp
Total production 10^3 tr oz	528	NAp NAp	462	NAp NAp

NAp Not applicable.

Sources: References 31 and 32.

Production from the lode deposits, however, had fallen for two basic reasons. First, 9 of the 11 new operations only accounted for approximately 84,000 tr oz of total annual production by 1981, or an average of less than 10,000 tr oz/yr per operation. Second, the high gold prices of 1980–81 caused the larger operating lode mines to decrease their mill feed grade for these years.

Production began turning around in late 1981. In the period from November 1981 through the first quarter of 1982, nine new lode gold mines came into production with capacities ranging from 10,000 to 70,000 tr oz/yr; the majority were in the 20,000- to 50,000-tr-oz/yr range. These new operations accounted for at least 300,000 tr oz of additional lode gold production in 1982 and, combined with the raising of mill feed grades at the larger operations due to lower gold prices, led to an increase of slightly more than 400,000 tr oz in total lode gold deposit production from 1981 to 1982. An additional 150,000 tr oz of lode production added between 1982 and 1983 came mostly from the final phases of expansion plans at producers instituted in 1981–82, since the net gain in the number of producers during this time was only two. During 1983 5 mines opened and 3 closed, leaving a net of 41 primary lode producers as of early 1984 (*32*).

Base Metal Deposits

Byproduct gold production from primary base metal mines has fallen steadily from 602,000 tr oz in 1965 to 455,000 tr oz in 1983. Table 46 gives a breakdown of gold production from base metal deposits by Province and type for 1973 and 1981. As shown, the decrease of approximately 66,000 tr oz from 1973 to 1981 coincided with a decrease in the total number of operations in production from 42 to 35; 13 mines closed (5 Pb-Zn-Cu, 6 Cu, 1 Ag, and 1 Cu-Fe) while 6 mines were opened (2 Pb-Zn-Cu, 1 Cu, 1 Fe-Cu, 1 Ag, and 1 Cu-Ag). The majority of the decrease occurred in Quebec and Ontario; two Pb-Zn-Cu and two Cu mines closed in each Province with no new operations put into production.

In 1981, approximately 73 pct of byproduct gold production from base metal mines was produced by only 12 of the 36 operations. These 12 all produced in excess of 15,000 tr oz/yr and were comprised of 3 Pb-Zn-Cu, 1 Ni-Cu, 1 Cu-Ag, and 7 Cu operations. As of early 1984, 11 of the 12 operations were still producing. Two major points concerning the economics of byproduct gold production from base metal mines can be made:

1. The economic viability of byproduct gold producers depends upon the primary and coproduct base metals being produced rather than the economics of gold.
2. Control of gold grades and recoveries is very limited.

Assuming that prices for copper, lead, zinc, and nickel reached their lowest levels during 1982–83, then byproduct gold production in Canada may have bottomed out at about the 450,000-tr-oz level. Combining this with the assumption that the 12 major producers represent a "core" of production during the worst of economic conditions, then annual byproduct production would have a low-level range of about 350,000 to 450,000 tr oz and a high-level range of 450,000 to 550,000 tr oz.

Placer Deposits

In the early to mid-1960's placer gold production in Canada was fairly steady at a level of 40,000 to 50,000 tr oz/yr, representing around 1 pct of total output. In 1967, a sharp drop occurred and placer production fell to below 10,000 tr oz/yr, remaining there until 1975. Since 1975, placer production has steadily increased. Production in 1983 totaled approximately 114,000 tr oz and represented 5 pct of total Canadian production. In 1973, when placer production for the year was only 9,804 tr oz, one sluicing operation in British Columbia and 32 sluicing operations in the Yukon Territory provided the bulk of production. The operations in the Yukon Territory accounted for 66 pct of the output, the one operation in British Columbia accounted for 32 pct, and a number of very small operations in Alberta, Manitoba, and Saskatchewan accounted for the remaining 2 pct (*31*). By 1981, nearly all the creeks in British Columbia and the Yukon Territory with a history of gold produc-

Table 47.—Demonstrated resource data for selected major Canadian primary gold operations as of January 1984

Classification	Number of operations	Recoverable[1] resource, 10^6 mt	Contained gold[1]		Recoverable gold	
			10^6 tr oz	Pct	10^6 tr oz	Pct
Major producing	14	111	22.0	NM	20.6	NM
Major developing[2]	4	132	20.0	NM	18.9	NM
Total	18	243	42.0	NM	39.5	NM
Underground ore	17	NM	37.9	90	36.1	91
Surface ore	5	NM	4.1	10	3.4	9

NM Not meaningful.
[1]Mill feed basis, includes adjustments for mining recovery and dilution.
[2]As of early 1984, includes 1 property in the financing stage.

tion had been staked. Because of the recent boom in placer production, it is difficult to estimate the average size of the more important operations. Indicated production capacities of the larger operations are only about 2,000 to 3,000 tr oz/yr. The major points to be made concerning placer production in Canada are—

1. Because of hoarding and other nonreporting, it is difficult to estimate placer production.
2. The majority of placer production comes from two districts in British Columbia (Atlin and Cassiar) and three districts in the Yukon Territory (Dawson City, Mayo, and Kluane Lake).
3. With gold prices above $400/tr oz, a steady annual placer production of 50,000 to 150,000 tr oz can probably be expected.
4. Many of the placer operations in Canada are reworking deposits for the third or fourth time, and many are only economical when treating a large volume of feed material.

RESOURCE OVERVIEW, 1984

Estimates of reserves and resources in Canada have increased greatly since the late 1970's. The Canadian Government estimate of 1984 reserves was more than three times higher than the 1978 estimate and 35 pct greater than the 1983 estimate. These 1983 and 1984 estimates of 27 and 36 million tr oz, respectively, are conservative and represent a minimum level of availability. The estimates are based upon information that is circa 1982–83 and by definition cover only "operating mines and deposits committed for production as of January 1 of each year" (*33*). The estimates probably cover mostly material that is considered to be economically minable by the companies submitting the information. It is believed that the estimates include both primary and byproduct sources of gold.

This study (table 47) analyzed a demonstrated gold resource, as of January 1984 (mill feed basis), of 22.0 million tr oz, contained within the 14 largest and most significant primary producing mines. These operations, with one exception, each contain in excess of 450,000 tr oz gold in the demonstrated resource. In addition, a 1984 demonstrated gold resource contained within three developing primary gold mines in the Hemlo District of Ontario and one potential large-scale surface mine is currently estimated at 20.0 million tr oz. Total Canadian primary demonstrated gold resources contained in the 18 major operations and deposits included in this study are thus estimated at 42.0 million tr oz. Based on the analysis, this contained gold is apportioned 90 pct to underground resources and 10 pct to surface minable resources. On a recoverable gold basis, the apportionment is basically the same, 91 pct underground and 9 pct surface, with the slight change due to different overall recoveries. Only 1 evaluated operation (a nonproducer) would be a 100-pct surface mine, whereas 14 operations would be 100-pct underground producers and 3 operations would produce from both surface and underground resources. The surface resource present at three underground producers is insignificant in total quantity, and it is expected that these operations will exhaust their surface material in a few years. This resource situation stands in sharp contrast to that in the United States, where a large majority of the resource is surface minable material.

The potential amount of demonstrated byproduct gold contained within 31 producing and nonproducing copper, lead zinc, and silver deposits totals approximately 15 million tr oz. However, a potential of only about 6 million tr oz is contained within currently producing operations, some of which are under severe economic pressure and are questionable future producers. This reduces the probable availability of this byproduct gold. In addition, byproduct gold grades are generally less than 1 g/mt, recoveries are less than for primary operations, the time frame of availability is considerably longer, and the relative share of byproduct to total production has fallen from 34 pct in 1980 to 20 pct in 1983 as base metal production has declined. The very poor performance of base metal prices has impacted severely upon a determination of economic reserves of gold associated with base metal production, as in the case of the aforementioned Canadian Government estimates. Taking this fact into consideration, together with the more recent information supporting this study's higher estimate of Hemlo gold resources, places these two sets of estimates in close relation to each other.

An independent estimate by Homestake Mining (*23*) based upon 1983–84 data places primary gold reserves in Canada at 51 million tr oz of contained gold. This estimate includes current producers, the major Hemlo developments, and a large number of smaller producers and potential producers. Reserve and resource estimated for Canada's large number of smaller producers and explored deposits (potential producers) are very difficult to quantify with any degree of accuracy. This 51-million-tr-oz estimate is considered to be a reliastic inference of the upper range of known potential primary gold resources in Canada.

Estimates of total contained gold resources in Canada thus range, circa 1983–84, from a minimum of 36 million tr oz of "total reserves" (official Canadian estimate for operations in production or committed for production as of January 1, 1984) through this study's estimates of 42 million tr oz of demonstrated primary gold resources, or 48 million tr oz of total demonstrated resources for both primary and byproduct operations, to potentially as high as 51 million tr oz of primary gold resources estimated by Homestake Mining. All three sets of estimates vary between 15 and 30 pct of each other, and differences are due mostly to definitions concerning the number and sizes of operations included in the estimate.

Figure 26.—Location of producing and prospective primary gold mining operations, areas of gold deposits, and historical lode gold mining districts in Canada.

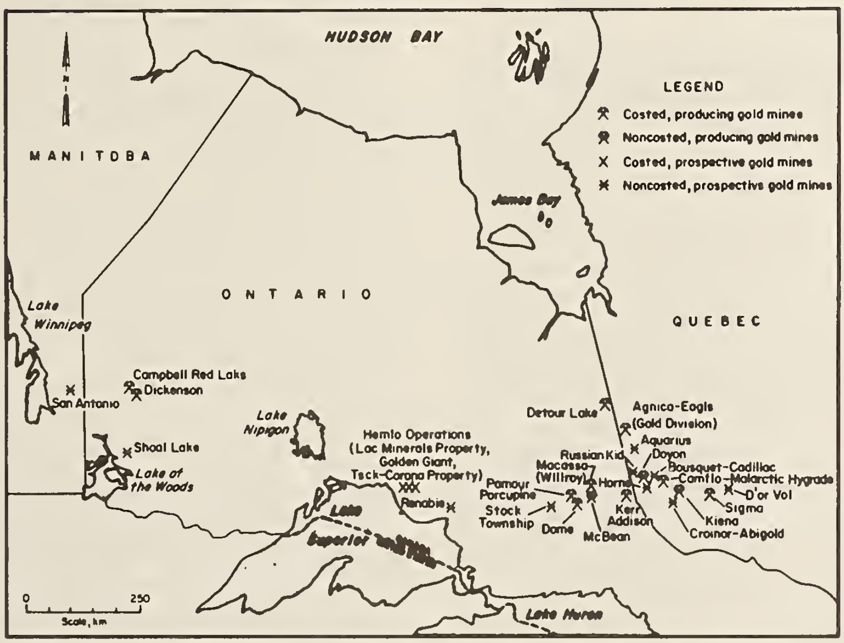

Figure 27.—Location of producing and prospective primary gold mining operations in Quebec, Ontario, and Manitoba.

Table 47 presents a summary of this study's 42 million tr oz of demonstrated resource for the 18 cost-evaluated producing and developing primary gold mines that contain the majority of total available gold. Figures 26 and 27 show the location of the evaluated operations.

In terms of annual ouitput, the 14 currently producing major operations accounted for over 58 pct (1.328 million tr oz) of total 1983 Canadian gold production and for 78 pct of gold production attributable to "auriferous quartz" (lode-type) deposits. These operations constitute the basic core of the Canadian gold mining industry. Because some operations involve 2 or more separate mines, these 14 major operations represent 22 of the 41 operating lode gold mines in Canada as of 1983. The remaining 19 lode gold mines not evaluated in this study accounted for about 375,000 to 400,000 tr oz of Canada's 1983 production. Only 7 of these 19 nonevaluated mines have annual production levels exceeding 25,000 tr oz. Indications are that the 12 smaller producers had only 4 to 5 yr of reserves at the start of production. Performing an accurate and detailed cost analysis for these small, probably short-lived, mines is very difficult and relatively unimportant by comparison to the world-class operations that were evaluated.

The three evaluated developing mines in the Hemlo District will represent the next significant increase in Canadian gold production between 1984 and 1990 and should account for an additional 676,000 tr oz of average annual output by 1989.

It cannot be overemphasized that gold is the dominant mineral in recent years in terms of Canadian exploration and new mine development. During the last 5 yr many small mines and three world-class operations have come into production. Many more deposits are under continued exploration and development planning with an eye toward eventual production. The three developing world-class operations at Hemlo that were evaluated could represent the beginning of a potentially large increase in Canadian gold production. Primary gold resources in Canada are expected to continue to expand for at least the near-term. Byproduct gold resources, and especially reserves, are a much more questionable issue, given the near-term outlook for base metal prices. The gold industry is in a very dynamic phase, not just in Canada but worldwide. All reserve and resource estimates will be subject to the same degree of dynamism and change.

PRODUCTION COST AND AVAILABILITY: CURRENT PRODUCERS

The 14 largest producing and the 4 most significant developing or potential mining operations were evaluated to determine long-run total production cost and gold availability as of January 1984. The summary results of these analyses are given in tables 48 through 51 and figures 28 through 33. The economic analyses are present in two sections. The first section constrasts the 11 largest underground producers with more than 10 yr of pre-1984 production with 3 new underground producers with less than 5 yr of pre-1984 production and 1 proposed large-scale surface mine. This section addresses the economics of new gold operations relative to those of older continuous producers. The second section focuses on the three developing mines of the Hemlo District in Ontario and underscores the very significant impact upon overall Canadian gold availability and annual production potential that the exploitation of the Hemlo District is expected to have in the near future.

Comparative Economics of Underground Production

In general, average ore grades for the producing operations are high, and their remaining producing lives, as determined by current demonstrated resource estimates, are usually 10 yr or greater. An estimated 23.482 million tr oz of refined gold is recoverable in total from the 15 non-Hemlo operations as of January 1984. Of this total, approximately 2.9 million tr oz is available from the proposed surface mine. Average annual available production totals approximately 1.5 million tr oz, of which 0.23 million tr oz is available from the proposed surface operation. Total required capital investments that must be recovered over the remaining life of each opeation range from $9.5 to $538 million for a total of approximately $1.8 billion in order to fully exploit their current 1984 demonstrated gold resources.

The relative contribution of per-ounce capital and operating costs to total cost is depicted in figure 28. Capital costs per ounce of recovered gold range from $22 to $136. Operating costs per ounce of recovered gold range from $112 to $526. Total operating plus capital costs per ounce range from $134 to $598. At the break-even level, long-run total cost estimate range from $138/tr oz to $614/tr oz, and at a 10-pct rate of return (fig. 28), cost estimates range from $168/tr oz to $647/tr oz.

The future availability of gold is heavily dependent upon new mine development as resources in older mines are exhausted. In Canada, three new world class underground mines have begun producing during the last 5 yr. Table 48 presents summary data on the cost determination analyses for these 3 new underground producers with less than 5 yr of pre-1984 production and contrasts it to similar data developed for 11 underground producers with at least 10 yr of pre-1984 production. This table details the relationship between the major total-cost-determining factors of mill feed grade (a measure of resource quality), available annual production (a measure of output quantity or resource flow), total recoverable gold (a measure of total product quantity or resource stock), the number of past and future producing years as of January 1984 (the time element), total capital investment to be recovered, and capital and operating costs per ounce of gold.

The most important distinction between new and old underground operations is in mill feed grade, which reflects the higher gold price levels of the late 1970's and early 1980's. The newer operations average 5.4 g/mt over their total demonstrated resource, compared with 11.4 g/mt for older producers. The three new mines account for 319,000 tr oz/yr combined output, or between 11 and 15 pct of expected Canadian production during 1983–86. Capital investments, as $102/tr oz recovered gold, are 62 pct higher than for the older producers, while operating costs, at $328/tr oz are 27 pct higher than for the older producers. As a result, berak-even total costs at the new producers average $100/tr oz recovered gold more than for the older producers.

The three new underground mines with less than 5 yr of past production will require prices well above the $400 base price in order to recover all costs over the lives of the operations and obtain a 10-pct long-run rate of return. These operations began producing in 1979 or later and were the results of exploration and development activity of the mid-1970's, which was initiated owing to the rapid escalation in gold price that began at that time. The long-run price outlook during the time that the production decisions for these mines were made was much more bullish than current gold prices would support. Two of the three new underground producers have average grades of 4 g/mt or less. This is the major negative element for this group of mines, given the relatively unfavorable 1983–84 gold prices.

At the new producer evaluated as a long-term predominantly underground operation that is currently mining surface material, this material represents 12 pct of the total demonstrated resource at this operation and is expected to be mined out by 1988, at which time production must commence underground. Although current economics

Table 48.—Comparative summary results of 1984 long-run cost determination analyses for underground Canadian mines

	5 yr or less past production (3 mines)		Greater than 10 yr past production (11 mines)	
	Range	Total or weighted average	Range	Total or weighted average
Operational data:				
Mill feed grade .... g/mt	3.4-11.0	5.4	2.7-21.2	11.4
Average annual output ...... 10^3 tr oz	50-144	319	37-216	936
Total availability[1] .... 10^3 tr oz	504-3,322	4,823	111-4,810	15,757
Producing years from Jan. 1984	8-23	NAp	3-40	NAp
Capital and operating cost data:				
Total capital investment[2] 10^6 dollars	$47-$307	$490	$9.5-$538	$992
Capital cost per troy ounce	$93-$136	$102	$22-$112	$63
Operating cost per troy ounce[3]	$248-$352	$328	$112-$526	$259
Total operating plus capital cost per troy ounce	$384-$445	$430	$134-$598	$322
Long-run total cost per troy ounce:				
Break-even (0-pct DCFROR)	$406-$441	$434	$138-$614	$334
10-pct DCFROR	$469-$574	$544	$168-$647	$386

NAp Not applicable.
[1]Refined gold estimated to be recoverable as Jan. 1984.
[2]Unrecovered capital investment in mine and mill plant and equipment, infrastructure, and development remaining as of Jan. 1984 and reinvestments through life of operation.
[3]Mining plus milling cost per ounce of refined gold.

Table 49.—Supporting data for figure 29: potentially available primary gold in 15 selected operations in Canada

Cost or price level per troy ounce	Break-even DCFROR		10-pct DCFROR	
	Available gold, 10^3 tr oz (cumulative)	Number of mines (cumulative)	Available gold, 10^3 tr oz (cumulative)	Number of mines (cumulative)
$400 or less	11,774	7	8,369	5
$500 or less	22,247	12	14,115	10
$600 or less	22,819	14	22,819	14
Over $600	23,483	15	23,483	15

Table 50.—Summary results of 1984 long-run cost determination analyses for three developing mines in the Hemlo District of Ontario, Canada

	Range	Total or weighted average
Operational data:		
Mill feed grade .... g/mt....	5.8–10.6	7.0
Average annual output .... 10^3 tr oz....	112–291	676
Total availability[1] .... 10^6 tr oz....	3–6.6	16.0
Producing years from Jan. 1984	26–34	NAp
Capital and operating cost data:		
Total capital investment[2] .... 10^6 dollars....	$138–$353	$804
Capital cost per troy ounce	$45–$54	$50
Operating cost per troy ounce[3]	$93–$125	$109
Total operating plus capital cost per troy ounce	$142–$179	$160
Long-run total cost per troy ounce:		
Break-even (0-pct DCFROR)	$153–$191	$170
10-pct DCFROR	$218–$294	$255

NAp Not applicable.
[1]Refined gold estimated to be recoverable as of Jan. 1984.
[2]Unrecovered capital investment in mine and mill plant and equipment, infrastructure, and development remaining as of Jan. 1984 and reinvestments through life of operation.
[3]Mining plus milling cost per ounce of refined gold.

Table 51.—Supporting data for figure 32: potentially available primary gold in 18 major operations in Canada

Cost or price level per troy ounce	Break-even DCFROR		10-pct DCFROR	
	Available gold, 10^3 tr oz (cumulative)	Number of mines (cumulative)	Available gold, 10^3 tr oz (cumulative)	Number of mines (cumulative)
$200 or less	16,042 (Hemlo)	3	0	0
$400 or less	27,816	10	24,411	8
$500 or less	38,298	15	30,157	13
$600 or less	38,861	17	38,861	17
Over $600	39,525	18	39,525	18

are marginal, the future of the operation is dependent upon the economics of underground production.

One entirely surface mine was evaluated under the assumption of production beginning in 1984; this mine would be marginally profitable at $400/tr oz gold despite a low average grade and high capital costs. These detriments would be offset by relatively low surface mine operating costs per ounce of recovered gold resulting from economies of scale at high annual production rates. In the Western United States, the economics of gold mining have come to favor large-scale, surface-minable material; however, in Canada the potential of the future will still lie with high-grade underground producers.

Total Potential Gold Availability

Figures 28 and 29 and table 49 relate long-run total cost to cumulative availability. As shown, approximately 50 pct of total recoverable gold from the 15 operations is available at a break-even price of $400, while only 35 pct is available at $400 under the 10-pct-rate-of-return criterion. All of the underground operations breaking even at $400 or less are older producers that have remained in continuous operation. At a break-even price of $500, fully 97 pct of total gold is available.

In contrast to the availability position of Canadian gold mines under a break-even cost-price scenario, rate of return analyses performed using a 10-pct discount rate determined that only 5 mines oprate profitably at $400, 10 mines at $500, and 14 mines a $600. Current 1984 gold prices are therefore not sufficient to maintain long-run profitability for two-thirds of the Canadian gold mines under these requirements. One reminder of this is the recent action taken at one of the highest cost producers herein evaluated, which indefinitely closed three of the six mines that comprised the total operation owing to the depressed level of 1984 gold prices. This operation is one of the lowest grade producers in Canada and as such is very vulnerable to falling gold prices (*34*, p. 10).

Annual Gold Production Potential

On an average annual basis, available mine production for all 15 evaluated mines (less Hemlo District operations) ranges from 37,000 to 223,000 tr oz/yr for a total of 1.255 million tr oz. Output from the 14 mines that actually produced in 1983 was approximately 1.328 million tr oz, or around 58 pct of Canadian production in that year. Byproduct gold production contributed 20 pct to 1983 output, while production from smaller hard rock gold mines and placer operations accounted for the remaining 22 pct. The 14 evaluated producing operations are considered to represent the basic core of the Canadian gold mining industry as of 1984. Based on the present trend in Canada, primary gold producers should account for higher percentages of annual output over the long term, given the increasing development of new primary mines such as the three developing Hemlo operations.

Annual output potentially available from these 15 major operations, from 1984 to 2000 at break-even cost-price levels of $400 and $600, is shown in figure 30. At $400/tr oz, approximately 1.0 million tr oz of annual production is available from 1985 through 1990, declining to 500,000 tr oz by 1996. This level of output is derived from nine operations, eight of which have been producing for many years. As ongoing exploration and development activity at these mines continues, the lives of the operations could be extended well beyond the life as determined by current estimates of demonstrated resources. At a cost-price level of $600/tr oz or less, a production level of approximately 1.5 million tr oz is available during the 1985–90. Available output at this cost-price level also declines steadily until 1996, at which time only six operations have remaining resources which represent approximately 820,000 tr oz of available production. The two highest cost operations are both fully exploited by 1990.

Three factors must be stressed. First, the analyses encompassed 14 of Canada's largest primary gold producing operations, representing approximately 58 pct of 1983 production. Second, mine lives were determined according to current estimates of demonstrated resources; however, the lives of all of these mines mayh be extended well beyond their current limits by further exploration. Third, the long-term annual amount of available byproduct gold production is very hard to estimate given the uncertain economic outlook for many of the base metal producers. In 1980, byproduct gold production accounted for 34 pct of the total; this percentage had dropped to 20 pct by 1983 and is expected to fall farther in the future.

This analysis so far has looked only at current gold producers and one nonproducing surface deposit. Three new, world-class operations in the Hemlo District of Ontario Province should begin to add substantially to Canadian output by 1985–86, thereby raising the relative share of primary production. The potential of this region is only now beginning to be realized. The very significant impacts in terms of both production and cost of these three operations are evaluated separately below.

HEMLO GOLD DISTRICT

Background

The Hemlo District is the most significant new gold discovery in Canada in at least two decades. The history of exploration efforts in the area goes back to 1947. The first major discoveries were made in 1981 by International Corona Resources. Resource estimates for the district have consistently increased since that time. To date, three properties have outlined resource estimates sufficient to warrant the development of major gold mines. The three properties are (1) the Teck-Corona property, (2) the Lac Minerals property (Ollman-Williams claim), and (3) the Goliath-Golden Sceptre-Noranda property known as the Golden Giant Mine.

The changing resource position of these three properties since 1981 underscores the very dynamic nature of gold exploration not only in Canada but in other major gold producing nations as well. For example, the first feasibility study of the Teck-Corona property, which encompassed exploration results through December 1, 1981, reported "reseves" of more than 1.0 million mt of ore (*35*). By late 1983, it was reported that the property contained 4.7 million mt at a grade of 12 g/mt (*36*, p. 23). This was revised upward again, and in 1984 it was reported that the property contained 8.4 million mt at 12.3 g/mt (*37*, p. B-38). Similarly, published resource estimates at the Lac Minerals property grew from 2.7 million mt of ore at 6.0 g/mt in early 1983 (*38*, p. 75) to 42.0 million mt at 6.9 g/mt by late 1983 (*39*, p. 442). Published resource estimates at the Golden Giant property have shown similar upward revisions over comparable time spans.

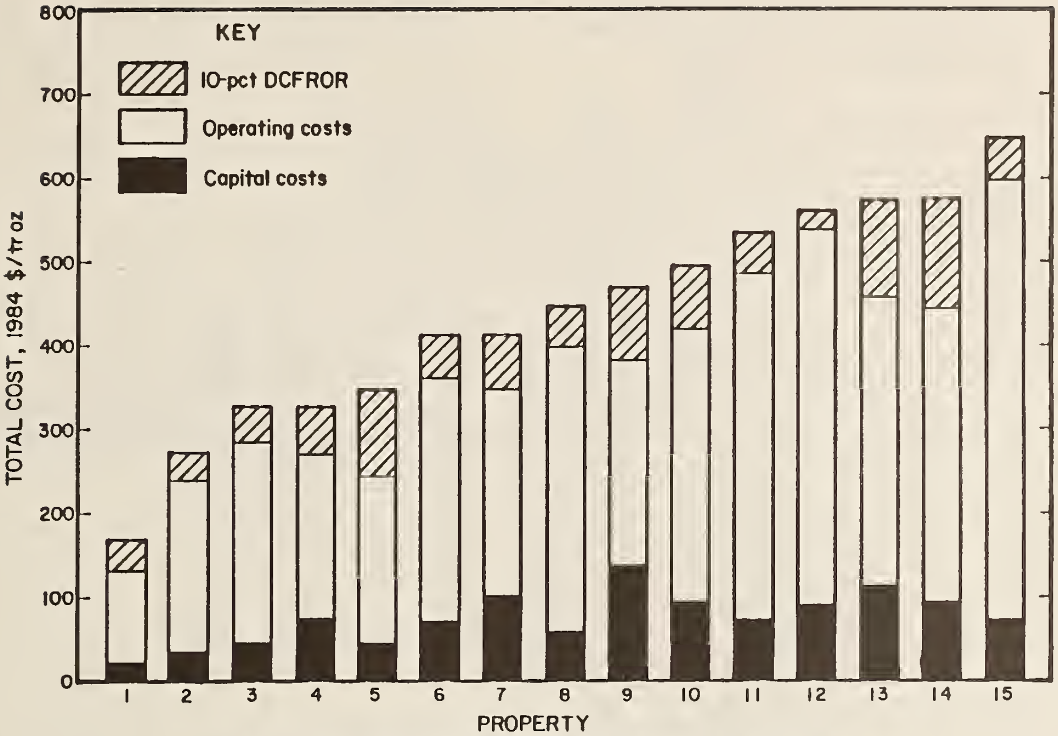

Figure 28.—Contribution of capital and operating cost to total production cost for 15 selected Canadian operations.

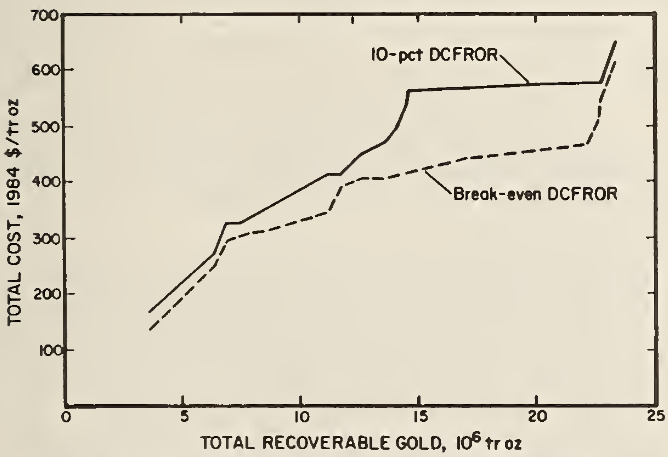

Figure 29.—Potential total Canadian primary gold available at various production cost levels from 15 selected operations as of January 1984.

This study currently estimates that the three properties in total contain approximately 72.5 million mt of recoverable ore with weighted average diluted grades from 5.8 to 10.6 g/mt. Total contained gold is approximately 16.4 million tr oz. Table 50 contains summary data of the economic analyses.

The results underscore the highly favorable economics of these operations. Break-even cost determinations range from $153/tr oz to $191/tr oz gold with a weighted average of $170; cost determinations at the 10-pct DCFROR level range from $218/tr oz to $294/tr oz with a weighted average of $255. Operating costs per ounce are quite low ($93 to $125), and given the large amount of available gold, capital costs per ounce are also low ($45 to $54). These cost estimates are significantly lower than those determined for all three of the newest gold producers in Canada and indeed are lower than those for all but the largest and highest grade older producers that were also evaluated. The major reason for the favorable economics at the Hemlo properties is the capability to mine high-grade material over very large mining widths, which allows the use of high-volume mining methods that are inexpensive by comparison to the methods that must be employed at most of the other underground gold mines in Canada.

Average annual production levels at the three Hemlo operations will range between 90,000 and 253,000 tr oz, and initial estimates of productive lives range from 26 to 34 yr. Total available gold from each property ranges from 3.0 to 6.6 million tr oz. As of early 1984, the three operations are estimated to have a total potential of producing 16.0 million tr oz of refined gold over their lives.

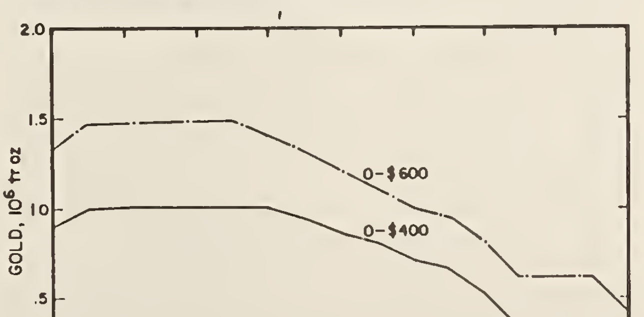

Figure 30.—Potential annual Canadian primary gold available at various break-even production cost levels from 15 selected operations, 1984–2000.

Impact of the Hemlo District Upon Future Annual Canadian Gold Output

The impact of these three operations upon annual Canadian gold output will be dramatic. Figure 31 shows combined annual output for these three mines for 1984–2010 at a break-even price-cost level of $200. According to this scenario, the Golden Giant Mine will begin producing in late 1984, the Teck/Corona property will have its initial production in 1985, and Lac Minerals (the largest of the three operations) will start producing in 1986. Full-capacity production, as initially designed, will be achieved by the Teck/Corona and Golden Giant Mines in 1987, with the Lac Minerals property expected to reach its full-capacity level in 1989. From 1989 through 2006 a combined annual output of 676,000 tr oz is anticipated. Production would decline thereafter if no further exploitable resources are added, which is considered unlikely. In any event, just the contained gold already demonstrated in these three properties will sustain a high level of production for about 20 yr.

In table 51 and figure 32, total Canadian gold availability is depicted for the original 15 evaluated properties combined with the available gold of the three Hemlo district mines. With 100 pct of the 16.042 million tr oz of recoverable gold at the three Hemlo operations available at a break-even cost-price level of $200/tr oz or less and below $300/tr oz at the 10-pct DCFROR level, these mines should come to represent the low-cost "core" of the Canadian gold mining industry. For example, when combined with the other 15 operations discussed earlier, the Hemlo operations increase the total available gold in Canada at the $400 cost-price level by 136 pct. At a 10-pct rate of return, the total available gold at the $400 cost-price level is almost three times higher when the Hemlo mines are included.

The effect of the Hemlo mines on future annual output will be to significantly raise available production from major Canadian gold mines at all cost-price levels. Figure 33 provides estimates of future production potential through the year 2000 for all 18 primary gold operations. Production from the three developing Hemlo mines will ensure that production from the major primary operations surpasses 2 million tr oz /yr during 1988–90 and remains above 1 million tr oz through the year 2000, even in the absence of further increases to demonstrated resources and annual capacity at the other properties.

Cumulative Canadian output during the 1989–2000 period, for all major mines producing at $410 tr oz or less, rises to 15 million tr oz with production from Hemlo, an increase of 85 pct. At $510 tr oz or less, cumulative output during the same period rises to 19.6 million tr oz, an increase of 69 pct. Production from the Hemlo gold district should ensure that Canada remains the third or fourth largest world gold producer for the foreseeable future.

TOTAL ANNUAL PRODUCTION POTENTIAL TO 1990, ALL SOURCES

This study concentrate upon 18 major primary operations which form the core of both current and future production potential. But the gold mining industry of Canada is complex and under dynamic growth with smaller operations beginning production and closing each year. An analysis of all primary producers in operation during 1981–82 determined that 19 additional lode gold producers were not cost-evaluated in this study. It was further determined that these 19 nonevaluated mines accounted for about 375,000 to 400,000 tr oz annual gold production and that only 5 of the 19 had annual output clearly exceeding 25,000 tr oz. Thus, the majority of the operations that were not evaluated are very small compared to those that were evaluated. In fact, a few of these mines were closed, either permanently or temporarily, by the low prices of the 1983–84 period and most of the remainder have reserves equivalent to only 3 to 5 yr of production.

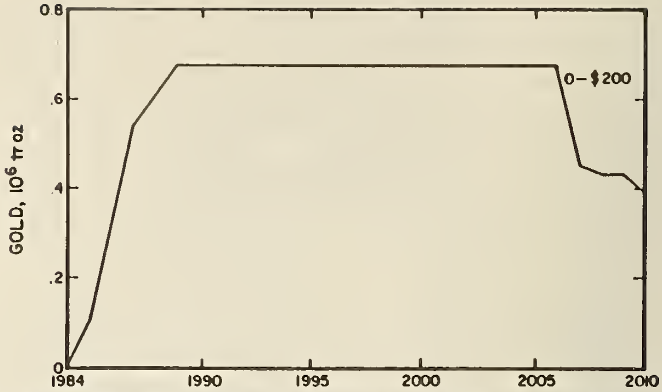

Figure 31.—Potential annual primary gold production from three developing mines in the Hemlo District, Ontario, Canada, 1984–2010.

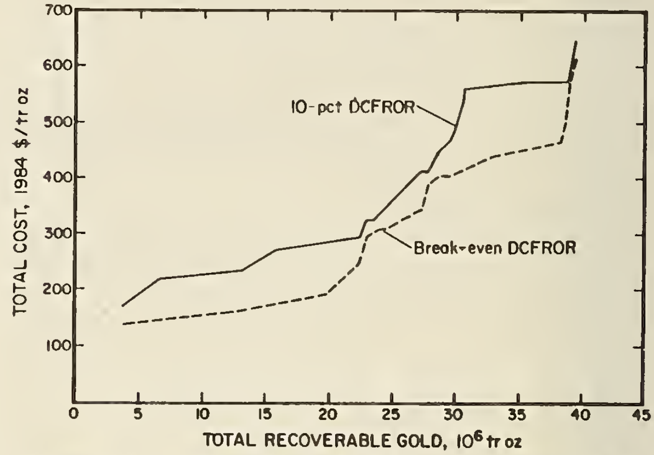

Figure 32.—Potential total Canadian primary gold available at various production cost levels from 18 selected operations as of January 1984.

A survey of the 1983–84 period has determined some 15 other smaller properties (out of a much larger total) that appear to have had enough encouraging exploration work to warrant either feasibility studies, that are undergoing mine development at this time, or that are in the early stages of production. Table 52 lists these 15 properties that are considered the most likely to be in production as an additional or replacement resource between 1984 and 1990. An approximate total production level of 470,000 tr oz/yr is possible by 1990 if all 15 are indeed brought into production. The individual estimates are based upon the most recent published information and are subject to revision as the studies and developments progress.

The following are some of the major economic aspects of the 15 properties shown in table 52:

1. All of these properties will begin production (if they are actually developed) with at least 5 to 8 yr worth of

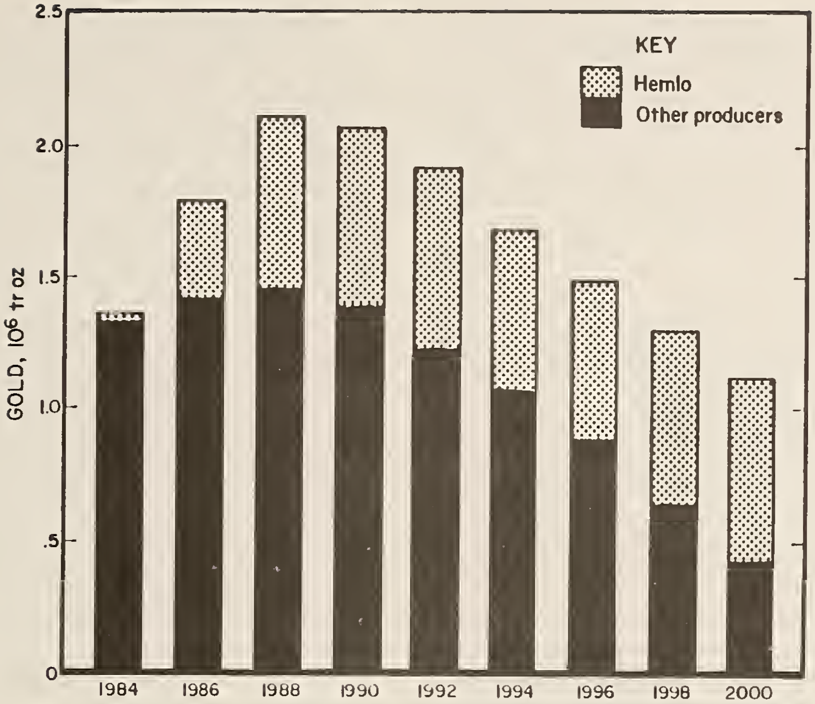

Figure 33.—Contribution of three Hemlo District operations to potential annual Canadian primary gold production, 1984–2000.

Table 52.—Canadian operations considered possible or probable primary gold producers during 1984–90

Province and property	Status as of 1983–84	Estimated additional annual production capacity, 10^3 tr oz	Estimated first year of production
British Columbia:			
Bralome-Pioneer	Under study	24	NA
Takla Lake	In exploration	30	NA
Manitoba:			
Agassiz	Under study	26	NA
San Antonio	...do	24	NA
Ontario:			
McBean	In production, April 1984	23	1984
Renabie (Cullaton Lake)	Expanding	60	1984
Shoal Lake (Duport)	In exploration	40	NA
Stock Township	Under study	35	1987–88
Quebec:			
Aquarius	Developing	25	1984
Bousquet-Cadillac	...do	23	1985
Croinor-Abigold	In exploration	40	NA
D'Or Val mines	Developing	23	1985
Horn Mine	...do	21	1985
Russian Kid	...do	28	1985
Saskatchewan: Bootleg	In production, early 1984	10	1984
Total	NAp	470	NAp

NA Not available.
NAp Not applicable.

reserves available, and a fair proportion will begin production with 10 yr or more worth of reserves.

2. All but one of the planned mines will be underground with expected feed grades ranging from 4.5 to 9.0 g/mt.

3. The planned surface mine is anticipating mill feed grades of 2.8 to 3.0 g/mt.

4. The range of production capacities is between 10,000 and 40,000 tr oz/yr gold with an average planned size of slightly over 25,000 tr oz/yr.

5. Because they mostly involve "new looks" at past producing operations, the "exploration" programs for the underground operations necessarily involve a high amount of underground development with extensive rehabilitation and extensions to previous workings to gain access to areas for exploration. Thus, most exploration and development programs for these deposits take 4 to 5 yr from the initial exploration stage through the feasibility study stage and are high cost, ranging from $3 million to over $10 million, depending, of course, upon the "target" size and amount of development required. However, because of the high exploration requirements, once a decision is made to go ahead with a project, the only additional capital requirements will be for mine equipment, milling facilities, and associated infrastructure items, and an average-sized operation will only take between 1.5 to 2 yr to get into full production.

For the following complete scenario of prospective future gold production, it has been assumed that byproduct gold production in 1990 will average between 350,000 and

Table 53.—Potential annual Canadian gold production by 1990, by type of operation

Type of operation	Total or range, 10^3 tr oz	Pct of total
Primary:		
Major producers (includes Hemlo District	2,100	60–68
Developing, in early stage of production, or considered probable for development as of circa 1984[1]	500–650	16–19
Base metal operations[2] (byproduct)	350–550	13–17
Placer operations[2]	100–150	3–4
Total	3,050–3,450	100

[1]Not subjected to complete demonstrated resource and long-term total cost evaluation.
[2]Assumed to remain constant at 1977–83 average levels.

555,000 tr oz, which is similar to output levels of the 1981–83 period. Again, it is difficult to estimate potential byproduct gold output since the near-term economic outlook for copper, lead, and zinc remains uncertain. Similarly, placer production (a minor contributor to the total and the most variable) is expected to range no higher than 100,000 to 150,000 tr oz in 1990.

To summarize the foregoing discussions, table 53 presents this study's estimates of the expected range of total gold production by 1990 in Canada from both primary and byproduct sources. The estimated range anticipates the development of new mines, the expansion of some current mines, and the permanent closure of others which for full potential would probably require a gold price of at least $450/tr oz to $500/tr oz. As shown, total Canadian gold production in 1990 could range between 3.0 and 3.4 million tr oz, which would represent the highest level since 1965 and an increase of approximately 1.0 million tr oz over 1984 production levels. Around two-thirds of this increase is expected to come from the development of the three major Hemlo properties. The remainder is expected to come from a number of smaller producers. The single most important point to stress is that the major primary operations that were cost-evaluated represent (at 67 pct) the largest source of assured long-term gold production and basically determine the overall economic competitiveness and growth prospects of the Canadian gold mining industry.

PRIMARY GOLD MILLING MAJOR OPERATIONS IN CANADA

A discussion of estimated mine operating costs at the 18 primary gold operations can be summarized by examining 20 separate mine operating cost estimates (17 underground and 3 surface mining estimates). Although a majority of primary gold production in Canada comes from underground mines, some of the operations utilize both surface and underground material in their overall production. Two examples of this would be the Giant Yellowknife operation, which mines surface and underground material simultaneously, and the Detour Lake operation, which is currently mining only surface material but is expected to progress to an entirely underground mine by the late 1980's.

Table 54 presents ranges of the 20 estimated mine operating costs for the 18 primary gold operations in Canada that were evaluated in this study. Included in the table are the number of estimated costs in the range shown, the mining methods and capacities represented in that range of operating costs, and a measure of overall mining productivity for the underground operations which includes underground labor and prorated surface and administrative labor.

Surface Mining

Surface mining of primary gold is not significant in Canada. As of late 1984, there were only two major mines in Canada producing gold ore entirely with surfacing mining (one of which was not evaluated for costs in this study and is not included in table 54). In addition, there was one major mine at which surface ore represents a portion of the mill feed. There is also one major proposed surface operation (shown in table 54) which, as of 1984, was still in the financing stage. Estimated waste-to-ore ratios of the surface mines evaluated for costs ranged from 0.56 to 3.5 mt waste per ton of ore. The estimated surface mine operating costs in Canada for the mines with capacities greater than 2,800 mt/d ranged from $1.25/mt to $2.70/mt material moved, depending almost entirely upon the mining capacity of the operation. The higher cost surface mine shown in table 54 represents a sporadic producer which has

Table 54.—Mining types, operating costs, capacities, and productivity for major Canadian gold operations

Range of mine operating costs, dollars per ton of ore	Number of operating costs in range	Description of mining methods within range	Capacities within range, mt/d	Estimates of overall underground mining production,[1] mt per worker-shift
Underground:				
$10.00 to $20.00	4	Long-hole open stoping, some shrinkage.	1,670–6,500	12.5–31.2
20.01 to $30.00	5	Cut-and-fill, shrinkage, room-and-pillar, long-hole and blasthole open stoping.	1,400–5,600	5.9–13.8
40.00 to $50.00	3	Cut-and-fill, long-hole and blasthole open stoping, shrinkage.	1,600–1,900	2.8–10.0
50.01 to $60.00	2	Open stoping, cut-and-fill, square-set stoping.	600–1,000	3.0– 3.5
Greater than $60.00	3	Cut-and-fill, narrow-vein shrinkage.	400–800	1.7– 3.0
Total	17	NAp	NAp	NAp
Surface:				
Less than $15.00	2	0.56-3.5:1.0 waste-to-ore ratio. Bench (berm).	2,800–15,700	NAp
Greater than $15.00	1	3:1 waste-to-ore ratio. Bench (berm).	300–350	NAp
Total	3	NAp	NAp	NAp

NAp Not applicable. [1]Includes prorated and administrative labor.

anomalously high surface mining costs due to the very low capacity and erratic nature of production from year to year. Surface mining costs in Canadian primary gold operations appear to be about 15 to 25 pct higher than surface mining costs at comparable U.S. operations, mostly reflecting a higher proportion of costs attributable to labor. It is not expected that surface mining will assume a major role in primary gold production in Canada in the near future.

Underground Mining

The vast majority of primary gold production in Canada has been and will continue to be produced by underground mines. It is very difficult to generalize or simplify a discussion of the underground mines producing primary gold in Canada, especially in regards to operating costs.

As shown in table 54, the underground operating costs estimated in this study range from slightly more than $10/mt to over $60/mt ore feed to the mill. Table 54 shows the three interrelated factors — the predominant mining method in use, overall underground productivities, and daily capacity — that have the greatest influence on the overall cost of mining. These categories are, in turn, directly related to the economic geology of the gold occurrence (grade of gold over a defined width of ore body) and conscious decisions on the part of the operation's management as to how to mine that defined ore body. Thus, the predominant mining method employed at various times may differ depending upon the amount of ore and the gold grade that management wishes to be supplied to the mill.

One actual (admittedly extreme) example of this interplay between desired ore feed grade, management decisions, and the resultant costs should suffice to give the reader a better understanding of the complex of factors involved in determining the overall cost of gold extraction.

In the last 1970's, a small (450-mt/d) underground mine was utilizing a relatively high-cost cut-and-fill mining method to produce ore grading a very high 12 to 13 g/mt. After the spectacular runup in gold prices during 1978, 1979, and early 1980, a decision was made by management to increase the operation's milling capacity by nearly three times, which meant that a comparable increase to the underground mining capacity was required. To achieve this increase in milling capacity, management decided to convert the mining method from the high-cost cut-and-fill method to a low-cost, high-tonnage long-hole open stoping method. (See table 54 for a comparison of the relative operating cost of these methods.) The change was instituted quickly, but possibly too quickly because the *recoverable* yield of gold at the mill fell from 12.92 g/mt of ore in 1979 to 7.8 g/mt in 1980 and to an extremely low 4.5 g/mt in 1981. This was a decrease of 65 pct in the *recoverable* grade over just a 2-yr period and a decrease of 44 pct in overall gold production from 1979 through 1981, despite a 60-pct increase to the mill's ore feed capacity. In addition, increased capital expenditure and declining output coincided with falling gold prices during 1980 and 1981. In 1982, to save the operation, the company decided to revert to its high-cost cut-and-fill method in the majority of the stopes, thus raising the feed grade back up to its normally high range (*40*).

It should be noted that most of the *major* primary gold producers in Canada that have come into production within the last few years, or that are planned for production in the near future, either utilize or plan to utilize low-cost underground mining methods such as blasthole or long-hole open stoping or relatively large-scale open pit methods. For example, of the nine underground mining costs in the two lower ranges shown in table 54, seven are operations that have been brought into production since 1968 or will be in production in the near future. This is partly a reflection of the increase in the price of gold leading to the economic extraction of lower grade ore bodies and partly a reflection of the discovery of a new type of ore body, the Hemlo type, which has amazingly large thicknesses (3 to 30 m) that can be mined utilizing low-cost, high-tonnage underground methods.

The depth at which major underground gold mines in Canada are operating does not, as of this date, appear to have a major influence on the overall mining cost. Hoisting distances as of the early 1980's range from about 200 m to around 2,200 m depths. The only major effect on mining costs caused by the depth of mining at the evaluated Canadian operations is due to losses of productivity at those operations which have to make more than one transfer of rock or more than one transfer of workers from the surface to the working area and vice versa

Direct plus indirect labor constitutes the major cost item in these Canadian underground operating cost estimates, averaging 48 pct for the seven long-hole or blasthole open stoping operating cost estimates and 63 pct for the 10 operations using either a mix of low- and high-cost mining methods or solely high-cost methods such as cut-and-fill, shrinkage and square-set stoping.

GOLD MILLING IN CANADA OPERATIONS

The 18 Canadian primary gold operations evaluated in this study represent 19 individual mills that are or will be treating ore from 25 individual mines and at least 26 different ore types. All but 4 of the 19 mills were in production as of 1983, with all 4 nonproducers in the financing or development stage as of 1983.

Of the 15 mills in operation in 1983, 7 were originally constructed during the 1930's, 3 were initially built in the 1940's, 2 were commissioned in the 1960's, and 3 were brought into production during 1980–82. As of 1983, only 1 of the 15 mills was accepting ore for custom milling from mines in the immediate vicinity, while another large mill was contemplating such a policy owing to projected depletion of its own ore reserves.

Design capacities as of the early 1980's for the 15 mills in operation ranged from 430 to 2,700 mt/d with 5 mills treating less than 1,000 mt/d and 10 mills treating more than 1,000 mt/d. In some cases, utilization as of the early 1980's was as low as 75 pct of design capacity. In general, this reflected hoisting constraints or conscious managment decisions rather than mill inefficiencies.

Estimated mill feed grades employed in this analysis for the 15 operating mills range from 3.4 to slightly more than 21 g/mt. Of the 15 mills evaluated, 12 were estimated to have overall gold recoveries of 90 pct or greater (straight average of 94 pct), while 3 either have or are expected to have overall gold recoveries of 83 to 85 pct. These lower recovery operations seem to reflect both that overall gold recovery drops off as the feed grade falls below 4 g/mt and that ores where the gold is intimately associated with pyrite appear to have lower recoveries.

Estimated mill operating costs range from $10/mt to close to $35/mt ore feed. Four of the mills have operating costs in the $10/mt to $12/mt milled range, seven have operating costs in the $12.01 to $17 range, and four have operating costs in the $17.01 to $35 range. The mills with operating costs below $12/mt have large capacities (1,300 to 1,700 mt/d) and simple flowsheets (crush, grind, vat leach, Merrill-Crowe-zinc dust precipitation, smelting to dore bullion). Those mills in the $12.01 to $17 range have more widely varying capacities (570 to 2,700 mt/d) and slightly more complex flowsheets with flotation and/or roasting of sulfides involved. Of the four mills with operating costs above $17/mt mill feed, two have relatively complicated flowsheets involving gravity concentration, flotation, and roasting; one operation has an extremely remote location; and two operations have relatively small capacities. Of note is the fact that all four of the mills with operating costs above $17/mt also have very good mill feed grades of greater than 10 g/mt ore milled.

Table 55 summarizes the methods of gold recovery in use as of the early 1980's at the major Canadian gold mills analyzed. As of 1981, only four operating mills had jigs in circuit with their grinding units to recover coarse, free gold. A high percentage of Canadian mills were utilizing a flotation and/or roasting stage for treatment prior to the cyanide leaching stage. These two points reflect the basic nature of most Canadian primary gold ores, in which the gold is highly associated with sulfide mineralization (especially arsenopyrite, pyrite, and pyrrhotite) and is usually present in a finely divided, disseminated state rather than as coarse grains. Also of interest is that 14 of the 15 mills utilize the Merrill-Crowe-zinc dust precipitation method of extracting gold from the cyanide solution, while only one mill utilizes the relatively new carbon-in-pulp method as the main[9] extraction method. The predominance of the Merrill-Crowe-zinc dust precipitation method reflects the fact that 12 of the 15 mills were constructed prior to 1969, before the period of the first major developments in carbon extraction of gold technology. Still, of the three mills added during 1980–82, two have opted for the more conventional Merrill-Crowe method over the newer carbon extraction methods.

In Canada, there are no large-scale heap leaching operations such as are found in the Southwestern United States, and none are foreseen in the immediate future. The long period of winter weather is a major negative factor in large-scale heap leaching. Also, all of the large-scale, economic heap-leaching operations in the United States are surface-mining mostly oxidized, primary gold deposits, a type of deposit that Canada does not appear to have in abundance.

Refining and Transportation

As of 1981, five gold refineries in Canada were accepting dore bullion (primary mine production) for refining along with gold scrap and residue (secondary sources). The five refineries and their estimated 1981 production capacities for refined gold production are shown in table 56.

[9]As of 1981, 2 of these 14 mills were using minor C/P circuits to recover gold from their precipitated roaster gases.

Table 55.—Summary of milling methods in use at major primary gold milling operations in Canada, early 1980's

Milling method (by major milling circuit)	*Number of mills using the circuit*
Comminution circuit:	
Crushing-grinding	15
Jig recovery of free gold	4
Treatment prior to extraction of gold by cyanide solution:	
Pre-aeration or other pretreatment prior to cyanide leach	4
Float for copper concentrate (for sale)	2
Float-regrind-roast concentrate	4
Float-regrind concentrate	1
Float-regrind pretreat concentrate	1
Float-roast concentrate	2
Float-roast concentrate-regrind calcine	1
None	4
Extraction of gold: Vat leach with cyanide solution	15
Precipitation of gold, production of dore bullion:	
Merrill-Crowe-zinc dust precipitation, smelt to dore bullion	14
Carbon-in-pulp (extract and strip gold from solution)-electrorowinning onto steel wool-smelt to dore bullion	1
Other processes:	
Electrostatic precipitation of roaster gases, recover gold by leaching and CIP treatment of precipitates	2
Leach tails from flotation	1
Production of As_2O_3 from roaster gases	3

In addition to the refineries listed in table 56, Inco Metals Co. has a precious metals refinery at Sudbury, Ontario, capable of producing about 225,000 tr oz/yr refined gold as a byproduct from treating the anode slimes resulting from the refining of copper and nickel. Noranda Mines Ltd. also has a precious metals refinery at Montreal East, Quebec, capable of producing about 720,000 tr oz/yr byproduct gold from anode slimes resulting from the electrolytic refining of copper.

The majority of the refining capacity shown in table 56 for treating dore bullion from the gold mines is conveniently located in relation to the Quebec and Ontario lode gold mines. The Royal Canadian Mint, located in Ottawa, is believed to handle most of the newly mined dore bullion in Canada. For analysis, it was assumed that all of the dore bullion produced at operations in Ontario, Quebec, and the Northwest Territories was sent to the Royal Canadian Mint at Ottawa for refining, with the dore bullion produced in British Columbia being sent to the refinery in British Columbia. The two operations producing gold-containing copper concentrates as well as dore bullion were assumed to be sending the copper concentrates to Noranda's smelting and refining facilities in Quebec. It is not clear where the proposed large-scale surface operation analyzed in this study will send its bullion if and when it is in production. However, indications are that its production level will be too high for the refinery in British Columbia, and its bullion will probably go to the Royal Canadian Mint refinery.

As shown in table 56, total Canadian refinery capacity

Table 56.—1981 capacities of Canadian dore bullion, scrap and residue gold refineries

Company	Province	City	Estimated production capacity, 10^3 tr oz/yr
Delta Smelting and Refining Co. Ltd.	British Columbia	Richmond	250
Englehard Industries	Ontario	Aurora	630
Johnson Matthey Ltd.	...do	Toronto	2,000
Royal Canadian Mint	...do	Ottawa	7,000
Trimount Refining and Smelting Inc.	...do	Richmond Hill	60
Total	NAp	NAp	9,940

NAp Not applicable.

in 1981 was nearly 10 million tr oz/yr refined gold from new dore bullion, scrap, and residues. The 18 properties evaluated in this study would account for no more than about 1.3 to 2.5 million tr oz/yr dore bullion production. Thus, it is believed that even with the Hemlo deposits coming on-stream in the late 1980's, there is sufficient refining capacity to handle the increases in gold production foreseen in Canada by 1990.

AUSTRALIA

HISTORICAL PERSPECTIVE

Total gold production between 1851 and 1980 from all Australian deposits is estimated to be approximately 190 million tr oz, or an average of 1.46 million tr oz/yr for the 130-yr period. Approximately 33 pct (63 million tr oz) of this total has come from alluvial mining of tertiary and recent river gravels. The remaining 127 million tr oz was produced from lode deposits (*41*, p. 141).

The first official recordings of gold discoveries in Australia were in 1851 in the Provinces of Victoria and New South Wales, although the first actual discovery had occurred as early as 1839 in Victoria Province. Of the discoveries in the two Provinces, the Victorian discoveries were the most important. Gold production from alluvial deposits in Victoria peaked in 1856 at 3 million tr oz/yr, and by 1860 attention had turned from alluvial production to hard rock mining in the Province. By 1891, production in the Victoria goldfields had fallen to about 500,000 tr oz/yr, and the search for gold had been expanded to other provinces, most notably Western Australia (*42*). By 1893, both the Kalgoorlie and the Norseman Fields (lode deposits) in Western Australia had been discovered and were producing. Table 57 provides a brief synopsis of the historical production picture in Australia. The table concentrates on reported historical production of Victoria Province and the Kalgoorlie Goldfield of Western Australia since these two areas have accounted for an estimated 118 million of the 190 million tr oz of total production.

Table 57.—Historical summary of mine production of gold in Australia, 1851–1983[1]

Year or period	*Occurrence or development*
1851	First official discoveries in Victoria and New South Wales Provinces.
1859	Production reaches 3 million tr oz/yr from Victoria Province.
1860's	Victoria Province produces an average of 1.6 million tr oz/yr, representing essentially 100 pct of Australian production and 40 pct of world production.
1890's	Victoria Province production falls to an average of 500,000 tr oz/yr. Western Australian Goldfields (Kalgoorlie and Norsemen) discovered and in production.
1903	Total Australian production reaches what proves to be a peak of 3.8 million tr oz. This coincides with the historical peak production at the Golden Mile (Kalgoorlie) of 1.0 million tr oz in 1903. Production in Victoria Province has increased to the 800,000-tr-oz/yr range.
1920's	Victoria Province production falls to an average of only 65,000 tr oz/yr for the decade. Kalgoorlie's production declines to 325,000 tr oz/yr, on average. The decline from production levels of the early 1900's was attributed mostly to rapid inflation of costs following World War I, which caused lower grade operations to close.
1950–67	Victoria Province's production further declines to an average of 44,000 tr oz/yr throughout the period. Total Western Australian production stabilizes in a range of 650,000 to 850,000 tr oz/yr.
1968–76	Increasing costs and low gold prices cause total Australian production to decrease from 787,000 tr oz in 1968 to an all-time low of 502,000 tr oz in 1976. Victoria Province's production reaches an almost negligible level of 2,050 and 6,600 tr oz in 1971 and 1972, respectively. Western Australian production decreases to a low of about 250,000 tr oz in 1976.
1977–83	Total Australian production increases dramatically from 502,000 tr oz in 1976 to 1.035 million tr oz in 1983. Western Australian production increases from 250,000 tr oz in 1976 to 750,000 tr oz in 1983. Increase coincides with large rise in the price of gold.

[1]Compiled from numerous sources and the authors' own estimates.

COMPOSITION OF MINE PRODUCTION OF GOLD, 1970–83

Figure 34 plots reported mine production of gold in Australia for 1970–83 (*2–3*). As shown, the initial reaction to free gold markets was an increase in production to 775,000 tr oz in 1972. However, the combination of a recession and declining gold prices caused production to decrease to 502,000 tr oz for 1976. The sustained increase in the price of gold from September 1976 into 1980 led to a slight rebound, yet by the end of 1981 production was only up 25 pct over the low level of 1976. It was only in 1982 and 1983 that the effects of higher gold prices, which caused a surge in new mine development, began to show up in substantially higher production levels, exceeding the 1-million-tr-oz/yr level in 1983. This was the first time that Australian mine production of gold had exceeded the 1-million-tr-oz mark since 1963 and represented more than double the 1976 production level.

The aggregate production values shown in figure 34 must be related to an operation-by-operation analysis to better understand the dynamics of the gold mining industry in Australia. With that in mind, table 58 provides "snapshots" of certain critical years during the period 1970–83.

Byproduct and coproduct gold production steadily declined on a percentage basis over this period, from 46 pct in 1972 to 41 pct in 1976 to 35 pct in 1979 and only 21 pct in 1983. The number of operations in this category, however, remained nearly constant. Throughout the 1970–83 period, the number of major gold producing operations (primary plus byproduct and coproduct producers) ranged from 9 to 13, standing at 12 as of 1983. From 1979 through 1983, the primary producers that could be considered major producers (the core of the industry) had only increased their annual gold output by 40,000 tr oz even though total Australian production had increased by 444,000 tr oz. Ninety percent of the remaining 404,000-tr-oz increase from 1979 through 1983 had come from as many as 21 minor primary gold operations (those with 5,000 to 30,000 tr oz of annual output), many of them representing new operations brought into production since 1981. Overall for 1983, 36 pct of total Australian gold production came from 7 major primary gold producers, 35 pct came from 21 minor primary producers, 21 pct came from byproduct gold producers, and 8 pct came from very small, primary gold producers (those producing less than 5,000 tr oz/yr).

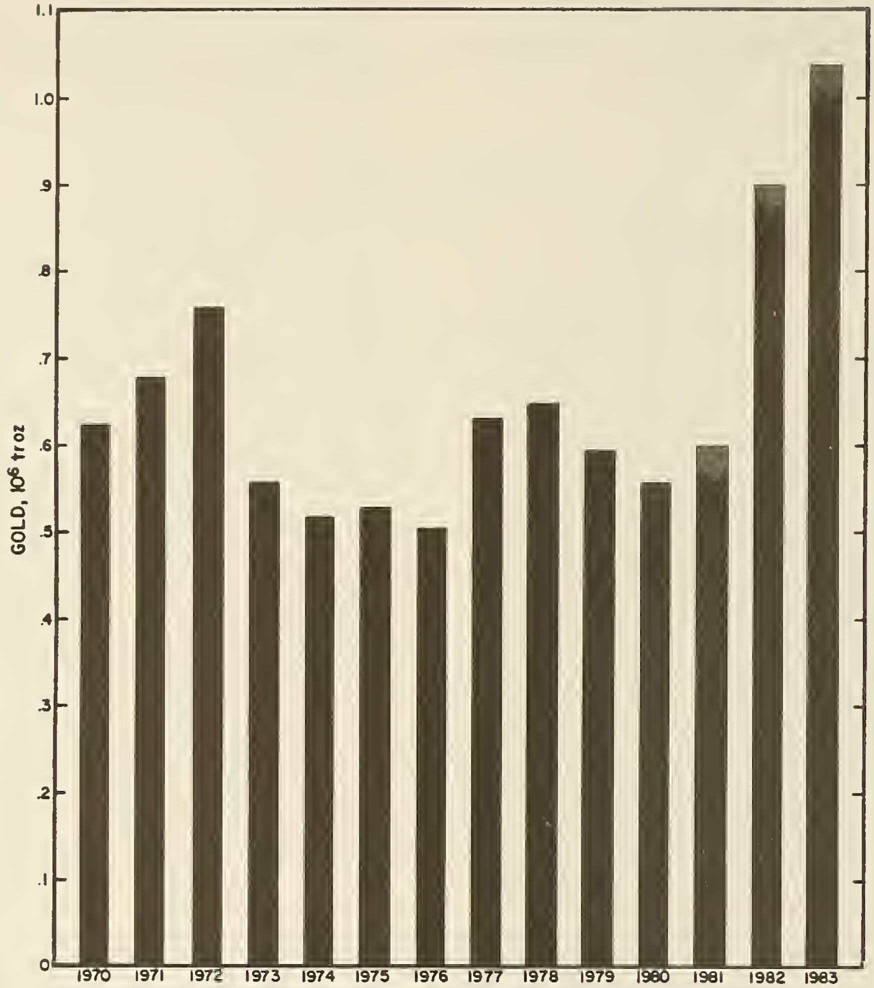

Figure 34.—Australian gold production, 1970–83.

Table 58.—Operational categorization of Australian mine production of gold in selected years[1]

Year	Total production, 10^3 tr oz	Description of operations producing gold
1972	755	95 pct (715,000 tr oz) of total production derives from 13 operations, with 5 of the 13 representing byproduct producers accounting for about 46 pct. The remaining 5 pct comes from 20 small, primary gold operations (producing less than 2,000 tr oz/yr, on average). Western Australia comprises 43 pct and the Northern Territory 33 pct of total gold production. Geographic distribution of major gold producers follows: Western Australia — 5 Au mines; Northern Territory — 1 Au-Cu-Bi mine, 1 Au mine; Tasmania — 1 Pb-Zn-Au mine, 1 Cu-Au mine; Queensland — 1 Cu-Au mine; New South Wales — 1 Pb-Zn-Au mine; Victoria — 2 Au mines.
1976	503	9 of the 13 major operations of 1972 are still producing. It is estimated that these major producers account for virtually 100 pct of total Australian mine production. Only 4 of the 9 major operations are primary gold producers. The 5 byproduct operations account for 41 pct of production. Western Australia comprises 42 pct and the Northern Territory 35 pct of total gold production. Geographic distribution of major gold producers follows: Western Australia — 2 Au mines; Northern Territory — 1 Au-Cu-Bi mine, 1 Au mine; Tasmania — 1 Pb-Zn-Au mine, 1 Cu-Au mine; Queensland — 1 Cu-Au mine; New South Wales — 1 Pb-Zn-Au mine; Victoria — 1 Au mine.
1979	597	8 of the 9 major operations of 1976 are still producing. In addition, 1 new major producer, Telfer in Western Australia, has been brought into production since 1976. The 9 major operations of 1979 are estimated to account for 93 pct of total production (555,000 tr oz) with 6 pct coming from small primary gold operations, mostly in Western Australia. The same 5 byproduct producers of 1972 are still producing in 1979. Western Australia comprises 59 pct and the Northern Territory 25 pct of total gold production. Geographic distribution of major gold producers follows: Western Australia — 3 Au mines; Northern Territory — 1 Au-Cu-Bi mine, 1 Au mine; Tasmania — 1 Pb-Zn-Au mine, 1 Cu-Au mine; Queensland — 1 Cu-Au mine; New South Wales — 1 Pb-Zn-Au mine.
1983	1,035	An estimate of the distribution follows in troy ounces: 7 major, primary gold operations (over 30,000 tr oz/yr). Includes 6 operations in Western Australia — 305,000 tr oz; 1 operation in Queensland — 70,000 tr oz. 21 primary gold operations (5,000 to 30,000 tr oz/yr). Includes 18 operations in Western Australia — 330,000 tr oz; 1 operation in Queensland — 10,000 tr oz; 2 other operations — 25,000 tr oz. 5 byproduct operations (no production criteria). Includes 1 operation in Northern Territories, 1 operation in New South Wales, 2 operations in Tasmania, 1 operation in Queensland. Very small, primary gold operations (<5,000 tr oz/yr.). Includes unknown number of operations, probably at least 35 in total, majority in Western Australia.

[1]Compiled from numerous sources and the authors' own estimates.

MINOR PRIMARY GOLD OPERATIONS

None of the 21 minor operations producing in 1983 were in production prior to early 1981. Most of these operations came into production with only 5 yr or less of reserves and an average capacity of about 17,000 tr oz/yr. These operations, which required little time to be brought into production, are mostly open pit operations, and many of them use heap leach processing methods. They are characterized by low capital and operating costs and are very flexible in terms of operational characteristics. Many of the operations consist of several small deposits feeding a central or custom mill; thus, it is virtually impossible to keep accurate account of production costs, reserves, and resources at these minor producers.

To put the size of these minor primary producers in Australia into perspective, it is expected that by 1988, over 20 new operations of similar size will be required just to replace the 1983 production level represented by these minor, primary producers. Likewise, to add 350,000 to 400,000 tr oz of additional annual production from this category of operation would require that as many as 40 new operations be brought into production. It is believed that a gold price of $350/tr oz to $450/tr oz is a sufficient economic incentive for these minor, primary gold producers, but the generally small amount of resources available for treatment could be a major concern. It is possible, depending upon the price of gold, that these operations could account for 500,000 to 700,000 tr oz of production in any given year, but it would probably be difficult to sustain this level very long.

MAJOR BYPRODUCT GOLD OPERATIONS

The five major byproduct gold producers in Australia that have produced throughout the 1972–83 period are the Tennant Creek, Mount Chalmers, Broken Hill, Rosebery/Hurcules, and Mt. Lyell operations.

At the Tennant Creek operations of Peko-Wallsend in the Northern Territories, overall production of gold declined from 208,000 tr oz in 1972 to 115,000 tr oz in 1983. However, the company felt, as of 1980–81, that it had a good chance of finding at least four or five ore bodies similar to the Warrego ore body (*41*, p. 141). It is believed that, if found, these would be utilized more as replacement mines to prolong the life of the operations rather than to increase production dramatically. At present, the mine has 11 yr worth of proven reserves.

The Mount Chalmers operation is a copper mine that produces 30,000 to 40,000 tr oz/yr gold. Estimated reserves at this long-time producer represent only about 2 to 3 yr worth of production. The other three major byproduct gold producers in Australia all have 10 to 30 yr worth of proven reserves.

Based on the proven reserve situation described above, it is expected that the 1979–83 level of byproduct gold production of 200,000 to 220,000 tr oz/yr should be easily maintained for 10 to 20 yr; however, unless new discoveries are made, there is very little room for major increases in byproduct production above that level.

RESOURCE OVERVIEW, 1984

The level of demonstrated gold resources in Australia has been changing rapidly over the last few years as exploration and development activity have intensified. As a consequence of this high level of activity, any estimate of gold reserves or resources will likely be outdated in a very short time.

The Australian Government estimated "demonstrated economic resources" of gold as of December 31, 1979, at approximately 9.0 million tr oz. As of December 31, 1980, this estimate was revised upward to 10.7 million tr oz. Total identified resources at that time were estimated at 14.0 million tr oz. An additional 4.8 million tr oz was classified as "contained in potential ore presently being developed." (*43*, p. 171).

A summary of the aggregate resource data estimated for this study is listed in table 59. For this study, a 1984 demonstrated resource of 6.7 million tr oz of contained gold was estimated for the seven largest primary producers. In addition, seven primary lead-zinc and copper properties were estimated to contain approximately 2.5 million tr oz of byproduct gold. Also reported in this study are preliminary estimates of approximately 11.0 million tr oz of gold contained in 17 other new properties in various stages of exploration and development, or in producing mines that were too small to meet the established criteria for complete economic evaluation. These latter resource estimates are reported separately and are not included as "demonstrated" resources owing to the absence of sufficient data to enable a more complete geologic verification of the resource estimates. The Olympic Dam/Roxby Downs project and the Deep Leads project are listed separately owing to their very large estimates of around 60.0 million tr oz of potentially contained gold. Figures 35 and 36 show the location of major primary and byproduct gold properties in Australia, designated by production status and inclusion in the cost analyses.

GOLD AVAILABILITY AND PRODUCTION COST EVALUATION: SEVEN MAJOR PRIMARY PRODUCERS

The seven evaluated primary gold operations in total were estimated to contain approximately 64 million mt of demonstrated resources as of January 1984. Mill feed grades

Table 59.—Aggregate gold resource data for selected Australian mines and deposits, 1984

Classification	Number of properties	Contained gold, 10^3 tr oz	Recoverable gold, 10^3 tr oz
Major demonstrated primary producers	7	6,700	6,400
Other primary properties[1]	17	11,000	NAp
Byproduct gold producers	7	2,500	NAp
Total	31	20,200	NAp
Possible major gold producers:			
Olympic Dam and Deep Leads	2	60,000	NAp

NAp Not applicable.
[1]For details on name, current development status, and estimated annual output, see table 61.

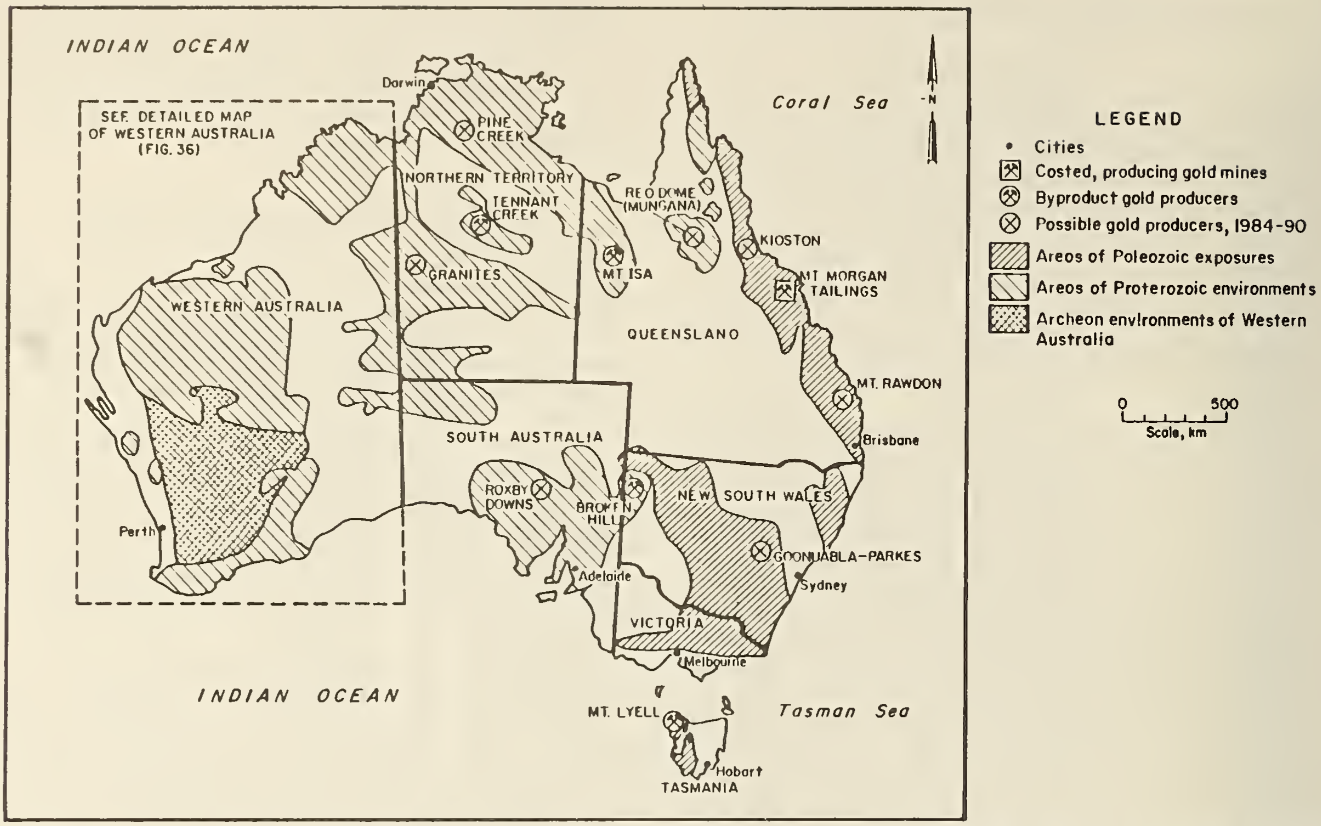

Figure 35.—Location of producing and prospective gold mining operations in Australia and areas of primary gold deposits.

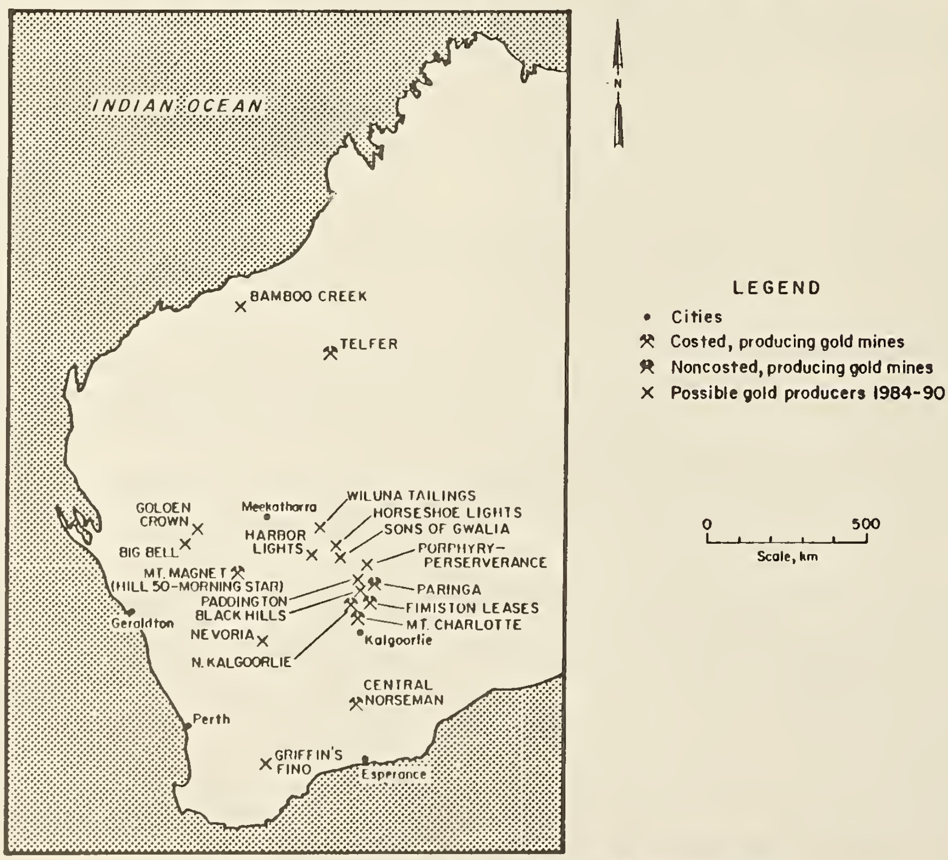

Figure 36.—Producing and prospective gold mining operations in Western Australia.

Table 60.—Summary results of 1984 long-run cost determination analyses for major Australian primary gold mines producing in 1983

	Entirely surface mining		Primarily underground mining		Grand totals
	Range	Total or weighted average	Range	Total or weighted average	
Operational data:					
Mill feed grade ... g/mt	1.0–5.0	3.6	4.0–12.0	7.0	NAp
Annual output ... 10^3 tr oz	45–65	110	25–120	304	414
Total availability[1] ... 10^3 tr oz	400–1,100	1,491.2	225–1,600	4,876.3	6,367.5
Producing years from Jan. 1984	9–17	NAp	6–23	NAp	NAp
Capital and operating cost data:					
Total capital investment[2] ... 10^6 dollars	$21–$51	$72.5	$30–$130	$357.3	$429.8
Capital cost per troy ounce	NAp	$48	$45–$135	$73	NAp
Operating cost per troy ounce[3]	$240–$310	$291	$150–$315	$222	NAp
Total operating plus capital cost per troy ounce	$290–$360	$339	$192–$344	$295	NAp
Long-run total cost per troy ounce:					
Break-even (0-pct DCFROR)	$325–$365	$353	$200–$477	$310	NAp
10-pct DCFROR	$340–$380	$368	$242–$513	$345	NAp

NAp Not applicable
[1]Refined gold estimated to be recoverable as of Jan. 1984
[2]Unrecovered capital investment in mine and mill plant and equipment, infrastructure, and development remaining as of Jan. 1984 and reinvestments through life of operation.
[3]Mining plus milling cost per troy ounce of refined gold.

were estimated to range from 1.1 g/mt (for a tailings reprocessing operation) to 11.6 g/mt.

Total gold contained in the 64-million-mt resource is estimated at 6.7 million tr oz, with total recoverable refined gold estimated at approximately 6.4 million tr oz. Two of the seven primary producers are old (primarily underground) operations which closed in the 1970's due to low market prices and rising production costs. With the rapid increase in gold price in the late 1970's, these mines were reopened with the expectation that prices would remain high or continue to increase. Recent decreases in the price of gold have again put the long-term economics of these two operations into question; both require long-term prices significantly above the $400 base price in order to break-even.

Another two of the primary producers are also old (mostly underground) operations that have remained in continuous production throughout their lives and are highly profitable at $400 gold, and two of the evaluated operations represent new producers that have been in production 5 yr or less. Of these two "new" operations, one is a surface mine that remains profitable at current gold prices and one is an underground producer that is considered subeconomic at the current base price. Also included in this analysis is a tailings project that has been producing profitably for several years. Average annual output for the seven evaluated major primary gold operations ranges from 25,000 to 119,000 tr oz/yr. The seven operations should represent a combined output of 458,000 tr oz of gold production as of 1984.

Table 60 presents summary data on the cost determination analyses for the seven primary gold producers. This table details the relationship between the major economic cost-determining factors such as mill feed grade (a measure of resource quality), available annual production (a measure of output quantity or resource flow), total refined gold potentially recoverable (a measure of total product quantity or resource stock), the number of future producing years as of January 1984 (the time element), total capital investment to be recovered, and capital and operating costs per ounce of recoverable gold.

In the case of the evaluated Australian surface mines, total capital investments to be recovered over the life of the operation range from $21 to $51 million, whereas in the case of the underground mines the range is from $30 to $130 million. However, owing to higher grade material at the underground mines, capital costs per ounce of recoverable gold are not significantly different. For the seven major primary gold producers herein evaluated, long-run total break-even production costs average $353/tr oz for surface production and $310/tr oz for underground production. Long-run production costs, which include a 10-pct rate of return on invested capital, average $368/tr oz for surface production and $345/tr oz for underground production.

Clearly, an operator interested in quick payback and low total initial capital investments will favor surface properties, especially small ones. This is why, as shown in table 58, a significant percentage of 1983 production is accounted for by some 21 small, primary gold operations, most of which are surface mines with typical outputs ranging from 5,000 to 30,000 tr oz/yr.

On an individual mine basis, this analysis indicates that the three new or reopened major underground operations in Australia represented gambles in that gold prices of around $500 are required in order for all costs to be recovered while attaining a minimum 10-pct rate of return. In the late 1970's, when the development or redevelopment decisions for these operations were made, the long-term price outlook was much more optimistic than that of 1984.

As was shown in the Canadian analysis, older producing mines that have remained in continuous operation possess a number of economic advantages. They have recouped most or all of their initial capital investments and generally have higher grade ore and larger annual output capacities. For these older producing operations, the production decision is largely dependent upon operating costs, with capital investment recovery representing only a small part of total production costs. For example, at one new producing operation, approximately $132/tr oz gold produced is required to recover $29.5 million in capital investments over 9 yr, whereas one of the established producers requires only $71/tr oz gold produced to recover $127.3 million in capital investments over 15 yr.

Separate analyses were performed in which long-run rates of return were determined for each of these seven mines given gold prices of $400, $500, and $600 per ounce, respectively, and a 10-pct discount rate. In all cases the price of byproduct silver production was held constant at $10/tr oz. The results indicate that at $400 gold, three of the seven operations have zero or negative long-run rates of return, i.e., these three operations require gold prices in excess of $400/tr oz for long-run profitability. Four of the seven mines (containing 76 pct of the 6.4 million oz of recoverable gold) are highly profitable at the base price of $400/tr oz.

At $500 gold, six of the seven mines are profitable by the criteria of this analysis with long-run rates of return

Table 61.—Australian deposits considered possible or probable gold producers during 1984–90

Province or Territory and operation	Status as of 1983–84	Estimated annual production 10³ tr oz	Estimated first year of full production
Northern Territory: Pine Creek	Feasibility study stage	50	Post 1985.
New South Wales: Goonuabla-Parkes	Explored deposit	[1]80	Post 1985.
Queensland:			
Kidston	In development, initial production 1985	190	1986–87.
Mt. Rawdon	Feasibility study stage	125	Post 1985.
Red Dome (Mungana)	do	70	Post 1985.
South Australia: Olympic Dam-Roxby Downs	Feasibility study stage, development approval received 1984	[1]105	Post 1989.
Western Australia:			
Bamboo Creek	In development	30	1988.
Big Bell	Explored deposit	45	Post 1985.
Black Hills	Feasibility study stage	40	1987.
Golden Crown	In development	35	1988.
Harbor Lights	do	100	1987.
Horseshoe Lights	In production	30	1984.
Nevorie	In development	25	1985.
Paddington	do	80	1988.
Peringa	In production	35	1984.
Porphyry-Perseverance	Feasibility study stage	30	1988.
Sons of Gwalie	In development	20	Post 1985.
Wiluna Tailings	In production	30	1985.
Total	NAp	1,120	NAp.

NAp not applicable. [1]Byproduct.

exceeding the 10-pct discount factor. Long-run prices in excess of $513/tr oz are required for all seven mines to operate profitably.

These analyses indicate that the three new or redeveloped mines may not remain in production for the entire life of their demonstrated resource unless long-run gold prices remain above $400/tr oz. The other four operations clearly demonstrate economic production at current 1984 prices.

The seven evaluated producers each have sufficient current demonstrated resources to allow for a minimum of 8 yr of production assuming sufficient gold prices. Two of the seven are expected to produce until at least the turn of the century but will account for only around 100,000 tr oz of combined output in 2000. These latter two mines are low-cost producers and are economic at current prices. Clearly, for Australia to maintain production at current levels will require the continued discovery and development of new mines. The potential for new mine development is examined in the following section.

MAJOR PRIMARY AND BYPRODUCT GOLD DEPOSITS AWAITING OR UNDER DEVELOPMENT

During the last few years, exploration and development activity in the Australian gold industry has been very dynamic. Many new exploration projects and development decisions have been reported in the literature in just the past 2 yr. Table 61 lists 18 major primary and byproduct gold deposits that have basically been fully explored and were in various stages of study or development as of 1983–84. Several of the properties have already produced small amounts of gold. The criterion for inclusion in this list was a minimum of 100,000 tr oz contained gold in the reported reserves. These deposits represent the largest contained gold reserves being reported for the entire country as of 1983–84.

Of the 18 deposits, 16 are primary gold deposits and 2 are byproduct gold products. Of the 16 primary gold deposits, 12 are located in Western Australia, 3 are located in Queensland and 1 is located in the Northern Territories. Ten of the 12 primary gold deposits in Western Australia will likely produce at a level of at least 30,000 tr oz/yr with an average output of 50,000 tr oz/yr. It is estimated that the 12 deposits in Western Australia could account for 500,000 tr oz/yr of additional gold production if they all come into production during the same time period. It is more likely that by late 1986 or 1987, 9 of the 12 will be in production and could account for around 350,000 tr oz of additional Western Australian production.

The four primary deposits located in Queensland and the Northern Territory are more questionable as to their possible development because they are all lower grade deposits in the range of 2.3 to 3.4 g/mt. As of late 1984, it appeared that one of the deposits would definitely be developed with another likely to be developed and the remaining two definitely "on hold." The three deposits in Queensland would represent an estimated 385,000 tr oz of additional annual gold production if all were brought into production in the same time period.

It must be emphasized that some of the individual property data included in this table must be considered speculative at this time. Within this list of 18 properties are two noteworthy mine developments, both proposed as surface mines, that appear to have a high probability of eventual production. One of these is the Harbour Lights project in Western Australia, which is estimated to contain up to 1 million tr oz of gold and could begin initial production by late 1985 (*44*, p. 230). The other project of note is the Kidston project in Queensland, estimated to contain around 2.2 million tr oz of gold, which could be in full production by late 1985; preliminary estimates for the first 5 yr of production average around 190,000 tr oz/yr (*45*, p. 199), which would make it Australia's largest producing mine.

One potential byproduct operation that warrants attention is the Olympic Dam/Roxby Downs primary copper prospect in South Australia. Olympic Dam is estimated to contain 2 billion mt of minable material grading 0.6 g/mt gold, or approximately 38.6 million tr oz of contained gold (*46*, p. 62). This deposit, if developed as presently planned, would have a very long life, probably in excess of 50 yr, and thus would not represent a major influence on annual Australian gold production since its annual gold output would probably be only slightly greater than 100,000 oz/yr. The development of Olympic Dam/Roxby Downs remains very much in doubt at this time, even though the project has received development approval. The project has some major technical and economic obstacles which must be overcome before any definitive development decision can be anticipated.

MINING METHODS AND OPERATING COSTS

A unique characteristic of the major Australian gold producers evaluated in this study, when compared to operations in other major gold producing countries, is the tendency for the operations to be combinations of surface and underground mines. For example, of the seven primary gold producing operations evaluated for costs in this study, two are 100-pct surface mining operations, two are 100-pct underground operations, and three are combinations of underground and surface mining operations. The two operations with 100 pct of their production by underground methods are large operations with annual ore capacities of 400,000 and 850,000 mt/yr; however, their ore grades are low (in the 4- to 5-g/mt range). The two operations with 100 pct of their production from surface mining methods consist of a conventional bench mining operation with annual ore capacity close to 500,000 mt/yr at a gold grade of over 7 g/mt, and a dredging operation that treats tailings from a prior milling operation at a rate of about 3.5 million mt/yr for a grade of slightly over 1 g/mt. The three operations utilizing a combination of surface and underground methods are fairly small, with total ore milling capacities ranging from 100,000 to 230,000 mt/yr and overall weighted-average mill feed grades of 4.7 to 10.8 g/mt.[10]

Of the five operations with at least some underground mining, two are using sublevel stoping methods, one uses a combination of cut-and-fill and shrinkage stoping, one uses an overhead stoping method, and one utilizes cut-and-fill with mill tailings. As of 1982–83, hoisting depths at the Australian gold mines were relatively shallow, ranging from 120 m to more than 1,300 m. Daily ore capacities ranged from 120 to 2,800 mt/d with 5 to 15 pct waste rock also being hoisted. Stoping heights for the nonsublevel stoping operations ranged from 1.8 to 3.0 m, while the sublevel stoping operations were dealing with stope heights of 3 to 10 m on average. Estimated underground mining productivities (including supervision) range from 4 to 15 mt per worker-shift. Estimated underground mining costs range from \$15/mt – \$20/mt to \$50/mt – \$60/mt. Labor costs are the single most important item in the estimated mining costs, representing 47 to 65 pct of the total.

It is difficult to categorize the major surface mining operations producing gold in Australia. As of 1981–82, annual ore capacities of the evaluated surface mines showed a wide range from 18,000 to 480,000 mt/yr, with waste-to-ore ratios ranging from zero to 40 mt waste per ton of ore. The larger pits are generally planned to bottom at a depth of 60 to 120 m. These depths presently appear to be the limit of any of the producing or planned surface gold mines in Australia. Most of the mining of overburden and ore in Australia is done by contractors since most of the surface mining operations begin with short projected mine lives and the reserves necessary to recoup major investments in mining equipment are not present. This situation, combined with relatively small capacities, fairly lengthy ore haulage distances to mills, and the somewhat remote locations of the operations, results in surface mining costs that are significantly higher (\$1.50/mt to \$1.90/mt material moved) then those at major U.S. surface gold mines. Direct labor costs are estimated to account for 25 to 35 pct of the total operating cost for the Australian surface mines evaluated in detail in this study.

[10] Underground ores grade 5.0 to 13.6 g/mt, while surface ores grade from 1.5 to 6.0 g/mt. The proportions of surface and underground material range from 90 pct underground and 10 pct surface to 62 pct underground and 38 pct surface.

METALLURGICAL METHODS AND OPERATING COSTS

Of the seven major primary gold operations evaluated, six are treating primary ore and one treats reclaimed tailings from a prior sulfide flotation operation.

The nine types of ore at these seven operations are treated in six mills. Two of these mills are using the carbon-in-pulp method of extracting gold from the solutions produced by cyanide leaching, while four use the conventional Merrill-Crowe method of extracting the gold from leach solutions. All of the mills treating primary ore contain a gravity separation-amalgamation circuit in closed circuit with their grinding stage to recover the coarse free gold in their ores, which is estimated to range from at least 10 pct to as much as 50 pct of total gold at individual operations.

Of the nine basic ore types involved, two are refractory ores and require roasting of flotation concentrates followed by cyanide leaching of the calcine resulting from roasting. Two other ore types are primary sulfide ores requiring production of a flotation concentrate which is then leached with a cyanide solution. The remaining ore types include two completely oxidized ores, two that are classified as "primary ores," and one consisting of sulfidic tailings. The operations that treat refractory ores are interesting in that they conduct a cyanide leach on the flotation concentrates prior to roasting and then use a second cyanide leach of the calcine after roasting of the concentrates. One of these operations then goes on to include a third cyanide leach, this time leaching the tailings from flotation.

Mill recoveries (total gold recovery) when treating nonrefractory, primary ores are high, ranging from 90 to 97 pct. The best recovery is at operations treating oxidized ore with high free gold content. Recoveries when treating refractory ores are lower, in the range of 83 to 90 pct. The recovery for the tailings retreatment operation is very low at 40 to 45 pct, basically reflecting the sulfidic nature of the original ore and the low grade of the tailings. A low recovery of only 83 pct is also indicated at one of the operations which treats a clayey, sulfide ore along with two different primary gold ores. The product of all of these mills is in the form of dore bullion, which is produced by smelting the various gold-containing precipitates (steel wool with electrowinning, "sponge gold" from retorting of amalgams, and zinc dust precipitate from the Merrill-Crowe process) with fluxes. These dore bullions are cast into bars or buttons in the 800- to 1,200-tr-oz range. The dore bullion from the operations analyzed ranges from 55 pct gold and 35 pct silver to 92 pct gold and 4.5 pct silver, the remainder is composed of base metals such as copper, lead, zinc, and iron. All of the dore bullion from the major operations was assumed to be transported by airfreight to one of the two major gold refineries in Australia. These refineries are located at Perth in Western Australia and at Melbourne in Victoria Province.

For the mills treating primary, nonrefractory ores, estimated operating costs (including smelting to dore bullion) range from about \$9/mt to \$19/mt ore treated. The lower cost operations (below \$15/mt) reflect higher tonnage operations (above 200,000 mt/yr). Generally, those operations treating refractory ores incur additional costs in the range of \$3/mt to \$5/mt which represent mainly the additional costs of flotation and roasting. It must be remembered, however, that this is simply a general trend noticed from comparison of the operations involved in this study. It is difficult to generalize about costs in the

Australian gold mining industry, especially when including costs in the administrative and general categories, since these categories reflect a variety of circumstances from relative remoteness, to physical layout of the operations, to company policy.

A few final points should be made regarding gold metallurgy in Australia. First, there were no large-scale heap leaching operations in Australia as of the 1983–84 period, although there were several small heap leaching operations with maximum capacity in the 20,000- to 30,000-tr-oz/yr range. Second, the operating costs developed in this study apply only to the larger scale milling operations (above 150,000 mt/yr ore feed) which are using vat leaching techniques. Third, several of the major gold mills in Australia evaluated in this study set aside some portion of their capacity for custom milling of ores from small producers in the vicinity of the mill.

REFINING AND TRANSPORTATION

As of 1981, four primary gold refineries were accepting gold bullion in Australia: one in Victoria Province, one in Western Australia, and two in New South Wales. The refinery in Victoria is located near Melbourne and has an estimated capacity to produce 160,000 tr oz refined gold and 320,000 tr oz refined silver per year. The refinery in Western Australia is operated by the Perth Mint and is located in the city of Perth. It has an annual capacity to refine about 600,000 tr oz gold and 65,000 tr oz silver. In New South Wales, Matthey Garrett Pty. Ltd. has a refinery at Kogarah capable of producing 320,000 tr oz/yr gold and 640,000 tr oz/yr silver. The fourth gold refinery accepting bullion was Broken Hill Associated Smelting Pty. Ltd.'s Port Pirie complex in South Australia, which has the capability to produce 6,500 tr oz refined gold and 900,000 tr oz refined silver per year, mostly from its own lead concentrates. A fifth (nonprimary) gold refining facility is located at Port Kembla in New South Wales, where Electrolytic Refining and Smelting Co., Ltd., produces about 65,000 tr oz gold and 450,000 tr oz silver per year from treatment of anode slimes resulting from copper refining.

The above capacities are circa 1981–82 and represent a total capacity to produce around 1.2 million tr oz refined gold and 2.4 million tr oz refined silver per year. The majority of the major, primary gold producers evaluated in this study send their bullion to the Perth Mint's refinery in Western Australia. A Government organization, the Gold Producer's Association (GPA), handles the insurance, refining, and marketing of gold bullion being sent to the Perth Mint. Although the GPA takes responsibility for shipment of the bullion from the mine site to the Perth Mint, the transport charge is paid directly by the mines. It appears that as of 1984, Australia's total capacity for gold refining was being pressured by increasing mine production levels.

BRAZIL

HISTORICAL PERSPECTIVE

Beginning in the late 17th century and continuing into the late 18th century, Brazil was the largest producer of gold in the world. Mohide (*4*, p. 129) reports an estimated production from 1691 through 1780 of about 24 million tr oz with 9.4 million tr oz being produced during 1741–60. Most of the production during the 18th century came from placer deposits in the southern part of the country (fig. 37). With placer production beginning to decline in the late 18th century, the Morro Velho Mine in Minas Gerais was developed in 1834. Since that time, this mining operation has represented the basic core of Brazil's reported (registered) gold production up to the late 1970's. Also during this same time period, Brazilian gold production has been consistently eclipsed by discoveries and developments in the United States, Australia, South Africa and Canada, so that as of the mid-to-late 1970's, Brazil was the 11th to 13th ranked largest producer in the world, as shown in table 62.

Several developments since the late 1970's have required a reexamination of Brazil's position in the world gold mining industry. As shown in table 62, estimates of Brazil's gold production show a tremendous fourfold increase between 1979 and 1980 with the higher levels of production continuing through 1984. This increase in production has elevated Brazil into the ranks of the top six producers in the world, following South Africa, the Soviet Union, and Canada, and close behind or essentially equal to the People's Republic of China and the United States. The interrelated factors that have caused or reflect this increase in Brazilian gold production are believed to be —

1. The increased U.S. dollar price of gold.
2. Increased access to the Amazon Basin region through improved infrastructure and modes of transport (e.g., helicopters).
3. The discovery of the Serra Pelada gold deposit.
4. Improved cruzeiro payment terms for Government purchases of gold output by small miners in the Amazon Basin.
5. Poor economic conditions leading to dislocation from normal industries.

These five factors have had two major effects on estimates of gold production in Brazil. First, all five of these factors have been responsible for what is essentially a gold rush into the Amazon Basin. This gold rush is similar in many ways to those in past world history, but it involves a geographic area of much greater size. Second, the fourth factor, improved cruzeiro payment terms by the Brazilian Government, has succeeded in attracting more of the out-

Table 62.—Estimated Brazilian gold production and world ranking, 1975–84

Year	Total production,[1] 10^3 tr oz	World ranking
1975	172	13
1976	240	12
1977	280	11
1978	301	11
1979	320	11
1980	1,300	4
1981	1,200	6
1982	1,500	8
1983	1,600	6
1984[2]	2,120	4

[1]Compiled from U.S. Bureau of Mines Minerals Yearbooks (*20*): 1976, 1980, 1982. All figures differ substantially from those appearing in latest available official Brazilian sources due to the inclusion of estimates for unreported production by small-scale operations (garimpeiros). Officially reported figures for major mines in 10^3 tr oz follow: 1978–129; 1979–107; 1980–131 (revised); 1981–415.

[2]Estimated (*47*, p. 2).

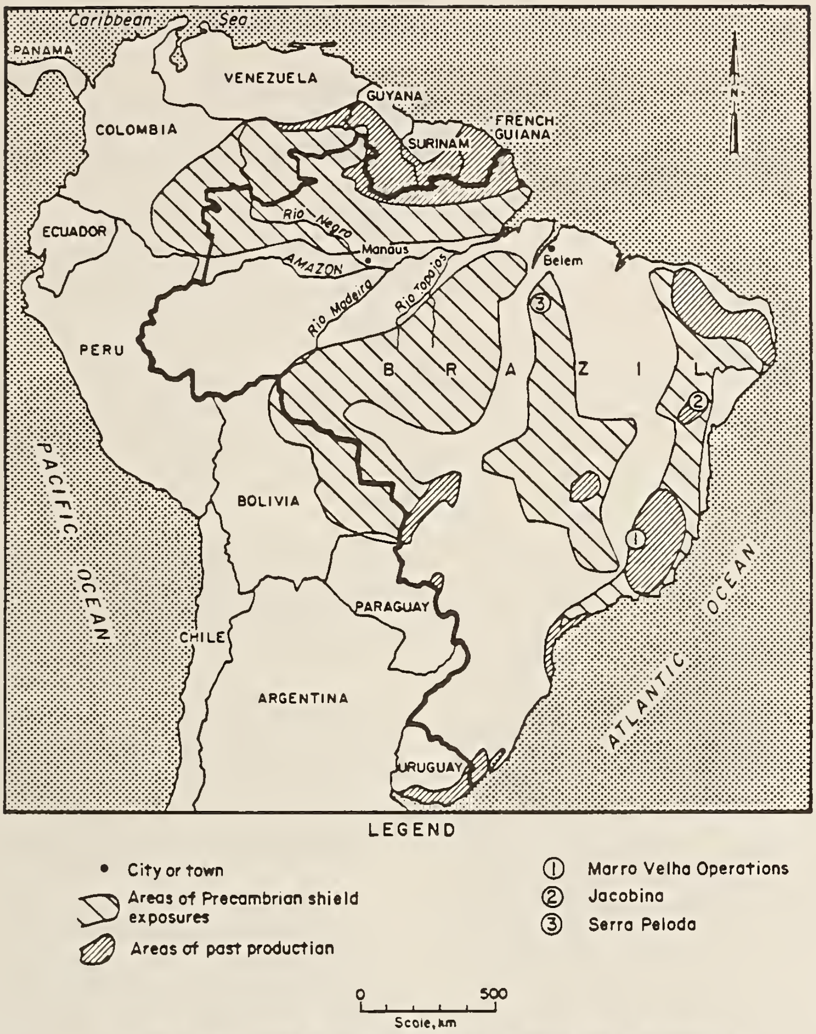

Figure 37.—Selected major nonalluvial gold mining operations and areas of primary gold deposits in Brazil.

put from workings in the Amazon Basin into the category of "registered" gold production, rather than being smuggled out of the country or not reported, as was prevalent in the past. This has led to higher reported production figures. According to the Finance Ministry of Brazil, so-called clandestine gold mining operations have dropped from 83 pct of total Brazilian production in 1979 to 30 pct in 1983 (*48* p. 281).

Some idea of the size and intensity of this Amazon Basin gold rush can be obtained by noting that the Serra Pelada deposit was discovered in February 1980. By September 1981, it was estimated that 50,000 garimpeiros (individual miners) were working Serra Pelada at its highest level of activity (*49*, p. 24). In a recent article in the Wall Street Journal, it was stated that 250,000 garimpeiros were operating in the entire Amazon Basin area, up from 97,000 3 yr earlier (*50*, p. 33).

SOURCES OF PRODUCTION AND PRODUCTION COSTS

Brazilian gold production for 1983 has been cited by several sources as 1.51 million tr oz, an increase of about 84 pct over 1982 production of about 803,000 tr oz. Expectations for 1984 were that 2.12 million tr oz would be produced (*48*, p. 281); however, the latest available figures indicate that gold production for 1984 will be slightly less than expectations at about 2.025 million tr oz (*50*, p. 33). Fully 85 pct of 1984 production will represent production from garimpeiros, with the remaining 15 pct being produced by organized companies. By comparison, in 1982 around 66 pct came from garimpeiro operations, while 34 pct came from organized mining companies. Thus, basically all of the increase in Brazilian gold production since 1982 has come from garimpeiro operations.

Table 63 categorizes the major sources of 1984 Brazilian gold production according to which operations are organized and which are not and also as to which are underground, hardrock operations and which are alluvial-eluvial-fluvial operations. As shown, only two primary gold operations, Morro Velho and Jacobina, are organized, company-run underground, hard rock operations and they account for only 209,000 tr oz (10 pct) of expected 1984 production. Less than 1 pct (16,000 tr oz) is produced from surface and underground copper operations conducted by Caraiba Metais. The remaining 1.895 million tr oz, or 89 pct, is produced from alluvial-eluvial-fluvial operations, 95 pct of which is produced by garimpeiro operations.

Because so much of Brazil's gold production represents small, nonmechanized production by tens of thousands of garimpeiros mining alluvial-eluvial-fluvial gold deposits,

Table 63.—Expected 1984 Brazilian gold production, by operation and type of mining[1]

	Expected 1984 production mt	10³ tr oz	Type of mining
Company operations:			
Morro Velho	5.0	161	Hard rock (underground).
Jacobina	1.5	48	Do.
Paranapanema	1.0	32	Alluvial-eluvial-fluvial surface).
Dragagem Fluvial	.6	19	Do.
Caraiba Metais	.5	16	Byproduct-hardrock (surface-underground).
Other companies	1.4	45	Unknown.
Subtotal	10.0	321	NAp.
Garimpeiro operations:			
Tapajos River	15.0	482	Alluvial-eluvial-fluvial (surface).
Cumaru River	10.0	322	Do.
Mato Grosso State	10.0	322	Do.
Rio Madeira	5.0	161	Do.
Gajas State	4.5	145	Do.
Belero area	3.5	113	Do.
Serra Pelada	3.0	97	Do.
Amazonas State	1.4	45	Do.
Maranhao State	1.0	32	Do.
Roraine River	.6	19	Do.
Amapa State	.5	16	Do.
Others	1.5	48	Unknown.
Subtotal	56.0	1,802	NAp.
Grand total	66.0	2,120	NAp.

[1]Compiled from various sources and the authors' own estimates.

it is impossible to analyze the majority of Brazil's gold production as to development schedules and production costs. Production levels vary greatly at these types of operations, and production costs in the normal sense of the term are meaningless. Therefore, an availability analysis that attempts to relate an expected total or annual level of gold production in Brazil to a long-term total production cost can address only about 10 pct of Brazil's 1983–84 production.

It is not possible to predict annual production, much less total potential availability, from the garimpeiros' operations. The long-term production cost of gold at these operations is essentially zero because the gold is produced in a more or less subsistence economy (i.e., no alternative form of employment) by semimechanized or manual methods involving very low-cost capital equipment such as motors to pump water and gravel. Some operations do use heavier equipment such as front-end loaders and trucks; this "mechanized" mining is technically illegal, according to the Government, but will probably increase in the future. The only cost that the Government incurs for that portion of the garimpeiros' production that is purchased is the marginal cost of printing new cruzeiros, which is also essentially zero. From a long-term availability perspective, the chief concern is that this high-grade, small-scale mining by the garimpeiros may render many deposits uneconomic to later mechanized mining, thus rendering some portion of the ultimate gold potential of the Amazon unavailable.

The Morro Velho underground mine and the Serra Pelada surface operation are estimated to contain approximately 10 million tr oz total gold. Morro Velho is an economic gold producer at a gold price of $400/tr oz. Based upon this study's estimate of demonstrated resources and current output levels, Morro Velho is expected to produce past the turn of the century.

The Serra Pelada operation, currently being mined by tens of thousands of garimpeiros, was evaluated as if it were operated as a large-scale, mechanized surface mine. The analysis under this scenario determined a long-term total production cost of less than $100/tr oz. The Government of Brazil has expressed a desire to convert Serra Pelada to a large-scale, mechanized operation run as a company endeavor, but has not pursued this option owing to the problem of having to deal with tens of thousands of displaced garimpeiros.

POSSIBLE NEW SOURCES OF PRODUCTION BEYOND 1984

With the spectacular increases in gold production that have occurred so far during the 1980's in Brazil, it is natural to speculate on how much higher Brazil's annual production level could go. As can be seen from the widely varying estimates of table 64, this is a difficult question to answer. This table presents different estimates of future Brazilian gold production to 1990 and the "best" estimates of actual gold production for 1980–84.

The 1980 Brazilian Government estimate of expected production in 1984 of 5.048 million tr oz has proven to be much too optimistic; estimated actual production was 2.12 million tr oz. It is difficult to say how much of the shortfall from the expectations of 1980 was due to the nonimplementation of the plans that the estimate was based upon, and how much was due to operational or economic factors. A comparison of the 1980 estimates with actual results should make one cautious about the two circa 1983–84 estimates of possible production levels in 1990. As shown, the Brazilian Government has mentioned a goal of producing nearly 13 million tr oz/yr by 1990 which would probably make Brazil the second largest gold producing country in the world, depending upon which estimate for the Soviet Union is used. The estimate for the same period by Mining Journal Research Services is much more conservative at an expected production of slightly more than 4 million tr oz/yr by 1990 and is probably more realistic since it only reflects a doubling in gold production between 1984 and 1990. Even this lower estimate of gold production would still make Brazil the third-ranked gold producing country in the world, behind only South Africa and the Soviet Union. For the near term, the Gold Institute predicts total Brazilian production of 2.581 million tr oz in 1985, a 22-pct increase over estimated 1984 production.

Table 64.—Varying estimates of actual and potential Brazilian gold production in selected years, thousand troy ounces

Year	Best estimates of Actual production	Brazilian Government estimate, 1980		Gold Institute estimates[3]	Other estimates
		1980[1]	1984[2]		
1980	1,300	NA	NA	NA	NA
1981	1,200	1,929	NA	NA	NA
1982	803	2,874	NA	NA	NA
1983	1,510	3,958	NA	NA	[4]1,607
1984	2,120	5,048	NA	1,920	[4]2,250
1985	NA	16,075	NA	2,581	NA
1986	NA	NA	NA	2,581	NA
1987	NA	NA	NA	NA	NA
1988	NA	NA	NA	NA	NA
1989	NA	NA	NA	NA	NA
1990	NA	NA	12,860	NA	[5]4,038

NA Not available.
[1]Reference 51, p. 55. Based upon expectations from a proposed plan to organize and control alluvial gold mining throughout Brazil; still not implemented as of 1984.
[2]Official Brazilian Government goal as of 1984 (*47*, pp. 2–3).
[3]Reference *2*.
[4]Reference 52, p. 79.
5Reference 3.

The question remains whether proposed expansions to existing 1984 producers plus additional production from undeveloped deposits can support either of the estimates of 1990 production shown in table 64. To answer the question, one should look at three distinct categories of Brazilian gold operations and deposits:

1. 1984 producers with production that can be accurately monitored, represented by the Morro Velho, Jacobina, Serra Pelada, and Caraibas Metais operations.
2. Deposits not in production as of 1984 with published grades or expected production levels.
3. 1984 alluvial-eluvial-fluvial producing operations, with 95 pct of the production representing garimpeiro operations and 5 pct representing company operations.

At the four 1984 producers where production amounts can be accurately monitored, the only announced expansion plans are for the Morro Velho and Jacobina operations, which are expected to increase production to the 390,000-tr-oz/yr level by 1988, an increase in annual capacity of 191,000 tr oz over 1984's level. No long-term expansion plans have been announced for either Serra Pelada or Caraibas Metais' operations.

A review of the literature as of 1982–84 resulted in a list of 11 prospective gold mining operations in Brazil where the expected annual production capacity can be roughly estimated. The list includes four individual alluvial operations planned by companies, six prospective primary, hard rock gold mining operations, and one porphyry copper deposit. The four alluvial operations should have productive capacities ranging from 3,000 to 25,000 tr oz/yr with an average size of about 10,000 tr oz/yr. The six primary, hard rock operations would probably have production capacities ranging from 12,500 to 150,000 tr oz/yr, with an average of 60,000 tr oz/yr. The porphyry copper deposit is reported to have gold grades sufficient to enable the operation to produce 95,000 to 130,000 tr oz/yr. Thus, these 11 prospective gold producers would probably be capable of producing 495,000 to 530,000 tr oz of additional gold annually if all were brought on-stream.

Additional gold production capacity from the expansions at Morro Velho and Jacobina and development of the 11 deposits mentioned in the previous paragraph would amount to 686,000 to 721,000 tr oz/yr. If 1984 total production of around 2.1 million tr oz is maintained, annual production by 1990, without any additional production from garimpeiro operations, would total 2.8 million tr oz. This would be 1.2 million tr oz less than the more conservative estimate shown in table 64 and nowhere near the higher estimate of nearly 13 million tr oz/yr by the Brazilian Government.

It is possible to propose various scenarios for additional production from other sources to bring the proposed production level up to 4 million tr oz/yr. The development of 44 additional deposits, comparable in size to those listed previously, would add about 1.4 million tr oz of annual capacity. Likewise, a 75-pct increase in 1984 garimpeiro production would add about 1.3 million tr oz of annual gold production. Thus, it appears that a level of production of 4 million oz/yr by the early 1990's in Brazil is not unreasonable to expect; however, a level of 13 million oz of annual production appears to be impossible to achieve without an extraordinary amount of new development within the next 6 yr.

RESERVES AND RESOURCES

In 1980, Companhia de Pesquisa de Recursos Minerais (CPRM), the Brazilian Government's mineral exploration company, estimated that there were 33,592 mt (1.08 billion tr oz) of contained gold in reserves of all types of ore, primary and secondary. This estimate of 1.08 billion tr oz of contained gold is important since the value is about 40 pct higher than this study's estimation of contained gold in South Africa's demonstrated resource. The 1.08-billion-tr-oz reserve is actually a resource total and was reported three different ways in the U.S. Embassy report (*53*, p. 2) from which the following descriptions were taken.

First, in terms of geographic location, CPRM reported that 0.421 billion tr oz are located in northeastern areas, 0.223 billion tr oz are located in the Amazonia region, 0.207 billion tr oz are located in the southeast area, 0.205 billion tr oz are in the central-western region, and 0.024 billion tr oz are in the southern area.

The resources were also split by CPRM into a primary portion, which represents initial mining and milling of ore, and a secondary portion, which represents alluvials and crushed rock. CPRM categorized 69.5 pct (0.75 billion tr oz) of the resource as primary material and 30.5 pct (0.33 billion tr oz) as secondary material.

The third way that CPRM described Brazil's resource estimate is the most important categorization in terms of normal methods of describing reserves and resources. In this categorization, CPRM described the 1.08 billion tr oz of primary and secondary gold resource as comprised of 0.023 billion tr oz of known reserves, 0.101 billion tr oz of geological reserves, and 0.956 billion tr oz of potential reserves.

It is not known why, but these values estimated by CPRM differ somewhat from data in CPRM's February 1980 booklet entitled "The Situation of Gold in Brazil" (*54*). In this publication CPRM places preliminary gold reserve estimates at a total of 0.744 billion tr oz of which 0.024 billion was in the defined reserve category, 0.192 billion was in a geological reserve category, and 0.528 billion was in a potential reserve category. There is no contradiction between the known reserve amount in the first set of estimates described and the defined reserve amount in the second set of estimates. It is only in the nebulous categories of "geological reserve" and "potential reserve" that the two estimates vary greatly. This discrepancy is understandable given that the geological reserve category is an estimate based on mathematical calculations from maps and aerial photos, while the potential reserve estimate involves an even higher level of uncertainty.

The defined reserve figure of 23 million tr oz of "known" gold reserve as of 1980 is as conservative as the 0.744 to 1.08-billion-tr-oz potential reserve estimate is liberal. It is probable that this official known reserve figure does not fully reflect new discoveries in 1980–83 and also does not reflect the nonorganized operations that, as already noted, accounted for over 85 pct of 1984 production.

The above resource estimates should be compared with the estimates of future production mentioned earlier. If the lower estimate for early 1990's annual production of 4 million tr oz is achieved (table 64) and maintained to the end of the century, at least 55 million tr oz of gold will have to be produced in 1984–99. Likewise, if the higher level of production of 13 million tr oz/yr by the early 1990's is achieved and maintained, between 150 and 175 million tr oz of gold will have to be produced in 1984–99.

U.S.S.R.

HISTORICAL PERSPECTIVE, 1754–1983

Major production of gold in the U.S.S.R. (then Russia) may have begun about 1754. An indication of this comes from a translation of a speech given by R. DeBatz in Atlantic City in February 1898. In the translation, DeBatz cites total gold production in Russia from 1754 through 1895 as 59.194 million tr oz distributed geographically as shown in table 65 (*55*, p. 452).

Table 65.—Gold production in Russia, 1754–1895, by geographic area

Area	Production 10³ tr oz[1]
Russia Proper (Finland and the Caucasus)	13
The Ural Region	16,249
Western Siberia	3,760
Eastern Siberia	39,172
Total	59,194

[1]Rounded from original estimates (*55*, p. 452).

As shown in the table, the bulk of the production up to 1895 had come from Siberia and from the Ural Region. According to DeBatz, in the 1840's, prior to the discoveries in California and Australia, gold production in Russia amounted to 40 pct of total world production, which would indicate a production level of about 700,000 tr oz/yr. By 1896, Russian production had risen to about 1.53 million tr oz/yr, yet it only represented about 14.5 pct of world production because of the discoveries in the United States, Australia and South Africa (*55*, p. 453). By 1914, Russian gold production had further increased to about 1.73 million tr oz/yr but represented only 6 pct of total world gold production (*56*, p. 275).

In the 5-yr period from 1915 to 1920, World War I and the Communist revolution resulted in a drastic decline to a production level of only about 100,000 to 200,000 tr oz/yr 1919–22. The gold mining industry became a state monopoly in 1920 and in 1923 began a slow rise toward its former production levels. However, it was not until 1932, with production of 1.8 million tr oz, and 1933, with production of 1.9 million tr oz, that the level of gold production finally surpassed the previous peak reached in 1914–15 (*56*).

Stalin announced in 1933 that production of gold in the Soviet Union could be easily quadrupled in a few years, indicating a target level of about 7 million tr oz, and, from 1932 through 1936 annual gold production increased to about 5.3 million tr oz, or 15.5 of total world production. Since 1936, all data on gold production in the Soviet Union have been treated as a state secret. At this time, total cumulative gold production in the Soviet Union from 1754 through 1935 approximated 100 to 110 million tr oz. However, from 1936 through the present, all gold production values for the Soviet Union have been estimated by Western experts and have varied tremendously, as will be shown. Depending upon which set of estimates is used, total cumulative Soviet gold production from 1935 through 1983 ranges from 300 to 400 million tr oz, for a grand total of anywhere from 400 to 500 million tr oz of cumulative gold production from 1754 through 1983.

Table 66 lists various estimates of Soviet gold production for 1970 and 1973–83; these estimates range from 5 million tr oz/yr to 13.5 million tr oz/yr. The Bureau of Mines estimates are the most conservative but also the most consistent. Beginning in 1981, the range of estimates appears to narrow to between 8.4 and 11 million tr oz/yr. This is very close to 9 to 11.25 million tr oz/yr estimated by Consolidated Gold Fields for 1980, which is probably a revision of the original 1974 estimates by Dowie and Kaser.

If the Bureau's estimate of 5.03 million tr oz for 1965 is accepted, and if the Gold Institute's estimate of 9.5 million tr oz for 1982 is correct, then the claim that the Soviet gold mining industry has undergone a revitalization, beginning with the eighth 5-yr plan of 1966–70 and continuing to the present, is valid (*58*, p. 6). As previous discussions have shown, revitalizations of gold production have occurred in Australia, Canada, the United States, and Brazil since the mid-1970's. Thus, it is possible that the Soviet Union has responded to increasing prices with higher production levels despite the general difference in the economic system.

Table 66.—Varying estimates of gold production in the Soviet Union for selected years (all estimates rounded to million troy ounces)

Year	Dowie and Kaser (*57*)	Consolidated Gold Fields	Mohide (*4*)	Kaser (*61*)	CIA (*61*)	Bureau of Mines (*20*)	Gold Institute (*2*)
1970	11.0	NA	NA	8.5	7.0	6.5	NA
1973	12.0	[1]5.0	NA	NA	NA	7.1	NA
1974	13.5	NA	NA	NA	NA	7.3	NA
1975		[2]12.9	7.7	NA	NA	7.5	NA
1976	NA	NA	7.9	NA	NA	7.7	NA
1977	NA	NA	8.0	NA	NA	7.8	NA
1978	NA	NA	8.0	NA	NA	8.0	NA
1979	NA	NA	8.4	NA	NA	8.1	NA
1980		[3]9.0–11.25	NA	NA	NA	8.3	NA
1981	NA	NA	NA	11.0	10.5	8.4	9.6
1982	NA	NA	NA	NA	NA	NA	9.5
1983	NA	NA	NA	NA	NA	NA	9.1

NA Not available.
[1]Reference 58. Estimated prior to the completion of the study by Dowie and Kaser.
[2]Reference 59.
[3]Reference 60.

Table 67.—Summary of 1970 operational data for Soviet gold operations from Dowie and Kaser's 1974 study (*57*)

	Average size, 10^3 mt/yr[1]	Number of operations	Recovery grade, g/mt
Small dredge	500	763	0.15
Washing plant[2]	170–340		
Large dredge	2,000	52	.07
Power shovel	1,700		
Underground placer	250	47	1.84

[1]Converted from cubic meters using a tonnage factor of 1.7 mt/m³.
[2]Includes gravel pump, monitor, bulldozer, and sluicing operations.

SOVIET GOLD PRODUCTION BY DEPOSIT TYPE

The most important source of gold production in the Soviet Union in the 1970's and early 1980's has been production from primary placer gold mines. Primary lode gold mines have been the next most important source, and byproduct gold production from copper, lead, and zinc operations represents the least important source.

The most informative study of Soviet gold production available to the authors of this study is that done in 1974 by Dowie and Kaser for Consolidated Goldfields Ltd. (*57*). The original study concentrated on estimates based on circa 1970 data. It is believed that this study was updated and enhanced in 1980 or 1981, but the details of the update, if done, are not available to the authors. Dowie and Kaser estimated that production in 1970 totaled 11.0 million tr oz. Of the total, 54 pct was estimated to be from placer production, 34 pct was from lode gold mines, and 12 pct was estimated to come from byproduct production, with 75 pct of the byproduct gold production coming from copper operations in the Urals. A summary of historical production by deposit type follows.

Placer Production

Of total Russian production from 1754 through 1895, 72.5 pct had come from Eastern and Western Siberia. The overwhelming majority of this production had come from placer deposits with vein deposits worked very little and always on a small scale. Very few dredges had been operated in Siberia before 1900, none with any success. It is believed that nonmechanized placer production practices continued until the late 1920's or early 1930's. This is supported by data in an article in Engineering Mining Journal of June 1935 (*56*) which contains estimates that in 1913 only 20 pct of total Soviet gold production was mechanized and in 1925 mechanized production was still only 25 pct. By 1933, fully 70 pct of production was mechanized, representing mainly the large-scale introduction of dredging and power shovel equipment (*56*, p. 278).

As of the early 1980's, placer production is probably still the most important source of gold, although its relative importance has declined with the increase in primary lode gold production since 1965–66.

Table 67 summarizes some of the operational data as estimated by Dowie and Kaser for their study. The number of operations of each type are Dowie's estimates as of 1970, and it is likely that equipment put on-line since then is of larger size. Dowie estimates that as of 1970 the waste-to-ore ratio at surface placers ranged from 1:1 to 5:1 with an average of about 2:1. To Dowie, the 5:1 stripping ratio appeared to be the maximum allowable before reverting to underground placer mining.

The grades of the placer operations, as estimated by Dowie and Kaser, are also shown in table 67. With an overall estimated production of 6 million tr oz from 1.07 billion mt placer feed material, the overall recoverable gold grade is about 0.17 g/mt feed material. These grades appear low when compared to Western operations at a similar time. In fact, Dowie and Kaser mention that the apparent grades for their estimates could be influenced by the methodology itself, especially on the low side. However, they also state (*57*, p. 13) that the derived estimates did agree with reported national totals. They further state (*57*, p. 14), with validity, that there is very little direct evidence of Soviet placer grades.

The grades given in table 67 of 0.07 g/mt for large dredges, 0.15 g/mt for small dredges and washing plants, and 1.84 g/mt for underground placers in the Soviet Union can be compared with the data in table 68, which shows typical grades at selected Western placer operations as estimated for this study. As shown, the three major Western

Table 68.—Placer grades at various evaluated operations in market economy countries

Country or State	Operational data		Recoverable grade, g/mt
	Status	Size, 10^6 mt/yr	
Bolivia	Dredge, producer	3.45	0.09–0.16
California	..do	6.4	.10
	Dozers and floating plant, nonproducer	3.7–4.7	.30–.60
Colombia	..do	30.0	.06

Table 69.—Important lode gold mining developments in the Soviet Union

Province	Deposit or mine	Start production	Gold production capacity, 10^3 tr oz/yr
Uzbekistan[1]	Zarafshan Mining Complex (Muruntau).	1971	2,600
Armenia	Armzloto (Zod Pass)	1971	320
Yakutia[2]	Nizhynyi Kuranakh Mining Complex.	1966–70	NA
Magadan	Dukut Lode	1980	NA
	Karakem Lode	Unknown	NA
	Nugodzer Mountains	Unknown	NA

NA Not available.
[1]Mill capacity of 50,000 mt/d to produce 50 to 60 mt/yr gold as reported by Cieslewicz (*58*, p. 8).
[2]Reported to be the largest gold mill in the world as of the early 1970's in terms of ore feed (*58*, p. 7).

dredging operations herein evaluated were treating material with grades of 0.06 to 0.16 g/mt as of the early 1980's with a weighted-average grade of 0.07 g/mt. Interestingly, this is the same grade as Dowie and Kaser estimated in their 1970 study for large Soviet dredging operations. There are no Western operations in this analysis that would be comparable to the small dredge, washing plant, or underground placer operations in the Soviet Union; thus, a comparison of relative grades cannot be made. It is certain, however, that the (circa 1970) grades of 0.15 g/mt for the small dredges and washing plants and 1.84 g/mt for the underground placer operations in the Soviet Union would be uneconomic at U.S., Canadian, or Australian wage and energy costs and with gold prices below $400/tr oz.

Lode Production

This is the category of Soviet gold production that is believed to have shown the greatest increase since 1965–66. However, this was also the category that showed the widest variation in Dowie and Kaser's 1970 production estimates. Their best estimate of production was 3.8 million tr oz, while their possible estimate was 6.4 million tr oz. Based on the few published estimates of production capacity at selected primary lode gold deposits in the Soviet Union, it appears that current (1980's) primary lode gold production is closer to the 6.4-million-tr-oz estimate.

Table 69 summarizes pertinent data on the most important lode gold developments in the Soviet Union since 1965–66. As shown, only two of the lode gold operations have had production estimates assigned to them, the Zarafshan (Muruntau) complex in Uzbekistan and the Zod Pass operation in Armenia. The latest estimates of annual production are 2.6 million tr oz and 320,000 tr oz, respectively, for a total of 2.92 million tr oz (*60*). These estimates are questionable, however, since another (*58*) has indicated that the design capacity at the Zarafshan complex as of 1977 was for only 800,000 tr oz/yr production. The milling complex at Nizhynyi Kuranakh was reported to be the largest gold mill in the world as of the early 1970's, this at a time when the Zarafshan gold mill was being brought on-stream at an indicated ore capacity of 50,000 mt/d as cited in the same source. The Zarafshan and Nizhynyi Kuranakh milling operations are both treating what has been classified as low-grade ore from large open pit operations. In fact, if the ore capacity and gold production values from Ciezlewicz's article (*58*) are correct, then the indicated recoverable grade at the Zarafshan operation was only about 2.8 g/mt ore feed and the Nizhynyi Kuranakh recoverable grade would probably be even lower. It appears that both mining operations are run more like a typical large-scale Western copper mine than a typical Western gold mine. The Zod Pass Mine is an underground mine in which it was planned to rail the ore 50 km to the mill, a possible indication of fairly high gold grades.

If it is assumed that the Nizhynyi Kuranakh milling complex is producing in the vicinity of 1 million tr oz (40 pct of Zarafshan's production), then these three operations (Nizhynyi Kuranakh, Zarafshan, and Zod Pass) account for nearly 4 million tr oz annual gold production. There could also be production from an unknown but possibly large number of other lode gold mines.

Byproduct Gold Production

Dowie and Kaser gave their best estimate of byproduct gold production for 1970 as 1.3 million tr oz/yr with a possible estimate of 1.8 million tr oz/yr (*57*). New estimates of byproduct gold production from copper and lead-zinc operations in the Soviet Union for 1977 and 1978 are reported to be 1.9 million and 2.0 million tr oz/yr, respectively, (*60*, p. 64). In 1977, 73 pct of this byproduct gold production came from copper ores and 24 pct came from lead-zinc ores. Also of interest is the estimate that in 1977, 97 pct of byproduct gold production from copper ores came from 13 mining operations while 94 pct of gold production from lead-zinc ores also came from 13 mining operations.

RESERVES AND RESOURCES

Even more enigmatic than Soviet gold production estimates are estimates of gold reserves and resources. According to the Mining Annual Review for 1974, potential reserves of gold in ore and placer deposits in the Soviet Union were estimated at about 200 million tr oz in 1970 with measured reserves sufficient for 16 to 17 yr of operation at the current (1970) production rate (*62*, p. 438). In 1977, potential reserves were again reported to be 200 million tr oz with measured reserves sufficient for 12 to 15 yr of operation at current (1977) production rates (*63*).

At the other extreme is an assessment, reported in an article on Siberia in Optima magazine, that "there is far more gold in the ground in Russia than in South Africa with economically mineable amounts estimated to be between 125,000 and 156,000 tons (4.02 to 5.02 billion ounces)" (*64*, p. 97).

Given that the Soviet Union comprises about one-eighth of the entire land mass of the world and the lack of information available to make assessments, this very wide range of between 200 million and 4 to 5 billion tr oz is probably the best guess that can be made about in situ gold reserves and resources in the Soviet Union. It should be noted, however, that at an estimated 1983 production level of 9.1 million tr oz/yr, it would take 439 yr to mine out 4 billion tr oz of in situ gold resources.

Table 70.—Estimates of annual Soviet gold sales, 1966–83[1]

Year	Estimated sales, 10^6 tr oz
1966	Negligible
1967	1.1
1968	.8
1969	Negligible
1970	Negligible
1971	2.2
1972	6.8
1973	9.0
1974	9.3
1975	8.1
1976	6.5
1977	12.9
1978	13.2
1979	7.4
1980	2.6
1981	9.7
1982	6.4
1983	2.9
Total	98.9

[1]1966–74 from Mohide (*4*, p. 116). 1975–83 compiled from various issues of Mining Journal. Estimates in the table use the higher estimate of any range estimates. Estimates in the table are converted from metric tons and rounded to the nearest hundred thousand ounces.

ISSUES CONCERNING SOVIET GOLD PRODUCTION

The immediate question for the Western World to ask regarding the Soviet gold industry is how much of a factor this one nation, having produced 400 to 500 million tr oz in the past and with a present production capacity in the range of 8.5 to 11.5 million tr oz/yr, can have on the world's gold market as it presently exists. Pertinent issues regarding this question are —

1. Can the Soviet Union overtake South Africa in terms of annual production?
2. How much refined gold does the Soviet Union presently have in aboveground reserves?
3. What has been the pattern of gold sales since the late 1960's?
4. If the Soviet Union does overtake South Africa as the world's largest gold producer, what would such an event mean?

This study will not attempt to address these issues completely; however, some perspective on all of the points can be given.

First, given that the real price of gold remains between \$400/tr oz and \$500/tr oz in 1984 U.S. dollar terms, South African gold production should follow the trend outlined in this study, which indicates that the first or second decades of the next century could see a very large decline in South African production from its present level of 21 million tr oz/yr. It is considered likely, given past estimates, that Soviet production will be between 5 and 15 million tr oz/yr at that time. Most of the circa 1980 estimates of production capacity suggest that, at most, the Soviet Union has probably only doubled its annual gold production since 1936. In fact, the Soviets have twice, in 1933 and again in the early 1970's, boasted that they would exceed South African production levels and have failed both times. It is questionable, therefore, whether they can accomplish this task, without a drastic decline in South African production. Their failure to accomplish this task during the 1970's, when South African production was decreasing at an average rate of 1 million tr oz/yr and at least 200 new gold deposits were being discovered in the Soviet Union, raises these doubts. Thus, it is not expected that the Soviet Union will overtake South African gold production until the dwindling of Witwatersrand Basin production occurs.

As to the second and third issues, most estimates of aboveground gold reserves in the Soviet Union as of the late 1970's ranged from 1,800 to 2,700 mt (58 to 87 million tr oz) with some estimates as high as 4,000 to 5,000 mt (129 to 160 million tr oz) (*4*, p. 121). This compares with estimated total Western gold reserves of approximately 3.0 billion tr oz and with official International Monetary Fund gold reserves, as of mid-1984, of over 900 million tr oz (*65*). The Soviet Union's estimated aboveground reserve of 58 to 160 million tr oz compares with estimates of annual Soviet gold sales that have ranged from negligible amounts to over 13 million tr oz from 1966 through 1983, as shown in table 70.

Finally, what would it mean if the Soviet Union became the largest gold producer in the world in the first or second decade of the next century? First, it would probably mean that South African production had fallen below a level of 10 to 15 million tr oz/yr and, most likely, that total world production had fallen proportionately from the levels of the early 1980's. Second, by the first or second decade of the next century, cumulative world gold production will probably have reached about 5 billion tr oz. With so much overhang on the world market, it is not likely that one country's annual production of 10 to 15 million tr oz would be a significant factor in the overall market.

OTHER IMPORTANT GOLD PRODUCING COUNTRIES

Table 6 summarizes 1983 production by categorizing the countries as either major, important, or minor producers. The six "major" nations that this study has discussed in detail (table 6) represented 84 pct of 1983 world production. Ten other countries had sufficient production to be classified as "important" producers. These 10 nations accounted for an additional 13 pct of 1983 world production. The remaining 3 pct is accounted for by 40 "minor" countries. This section discusses the 10 important producing countries in some detail, and then presents a brief discussion of possible new gold property developments in countries considered minor producers.

One of the 10 important countries, the People's Republic of China, produced 1.9 million tr oz gold in 1983. The other nine countries in this category had 1983 annual production levels ranging from 166,000 to 817,000 tr oz, or an average of 428,000 tr oz per country. The 40 countries in the minor category in total accounted for 1.9 million tr oz of gold production in 1983, an average of only 47,000 tr oz per country.

Table 71 summarizes annual production for the 10 important countries for 1975–83, with projected data for 1984. As shown, annual production from these countries increased by 2.6 million tr oz from 1975 through 1983. However, 70 pct of this increase is due to major upward revisions to rough estimates of annual production in the People's Republic of China, and these estimates may still be questionable. The other nine countries increased their combined output by only 774,000 tr oz between 1975 and 1983, or about 86,000 tr oz per country on average. Preliminary estimates for 1984 indicate that overall production for these nine countries should remain effectively the same.

Since so little information is available on gold production in the People's Republic of China, no further discussion of this country will be made. The remainder of this section will present brief discussions of important aspects of gold production in the other nine free world countries categorized as important producers.

THE PHILIPPINES

The Philippines has increased gold production by 315,000 tr oz (63 pct) from 1975 through 1983. Roughly two-thirds of total production is represented by byproduct production from primary copper mines. In 1982, 5 major mining companies with 10 primary copper mines accounted for effectively 100 pct of total byproduct gold production. Production of gold from primary gold operations is similarly concentrated in a small number of companies. Over 87 pct of total primary gold production came from just four mining companies with nine separate mines. At least 200,000 tr oz of the 315,000-tr-oz increase in production since 1975 can be accounted for by the development of the Masbate and Masara/Mapula primary gold operations and the Dizon copper project. Two major primary gold projects, the Paracale project and the Siana project, were expected to be in production by 1983, with annual outputs of 50,000 and 30,000 tr oz, respectively, although reported total Philippine production does not seem to reflect such an increase.

There are at least 12 potential copper operations in the Philippines that are well explored and well studied that could produce appreciable amounts of byproduct gold. The byproduct gold grades at these deposits are relatively good at 0.4 to 0.7 g/mt, but the copper grades at these potential projects are low at 0.4 to 0.54 pct Cu. If all 12 projects were brought into production, they could account for around 300,000 to 350,000 tr oz of additional annual gold production; however, their development is questionable at this time. As far as is known, all 12 of these developments had been deferred as of 1983–84.

This study evaluated three primary gold operations to determine demonstrated resources and production costs. The three operations are the Benguet operations (Antamok-Acupan-Atok-Kelly-Thanksgiving Mines), the Masbate operation, and the Paracale project. Total demonstrated resources for these three properties are estimated at 4.1 million tr oz (contained gold) as of 1984. Total recoverable gold is estimated at 3.5 million tr oz, with most of this total represented by the Benguet Consolidated operations. Long-run total production costs for two of the operations are in the $200/tr oz to $260/tr oz range, while the other operation has estimated total costs exceeding $475/tr oz. Average annual production rates for these three operations range from 50,000 to 120,000 tr oz. Current demonstrated resources are sufficient for Benquet Consolidated to produce past the turn of the century. The other two operations are estimated to have remaining productive lives of between 8 and 12 yr.

The Philippines does not appear at this time to have the ability to become a major gold producer. It is expected that future gold production potential will remain dependent upon the economics of copper production, which has continued to represent a majority of total (byproduct) gold production.

PAPUA NEW GUINEA (PNG)

In 1982, 98.5 pct of PNG's total gold production was byproduct production from the Bougainville copper mine. PNG's gold production has trended steadily upward from a recent low in 1980, although production in 1984 is estimated to have fallen slightly.

Future gold production is expected to increase substantially with the beginning of production at the Ok Tedi copper-gold project since May 1984. The first phase of this project entails the mining of a leached cap of gold ore that overlies the porphyry copper deposit. This cap is reported to contain approximately 3.1 million tr oz gold (*66*, p. 332). Ok Tedi is expected to produce, on average, around 600,000 tr oz/yr gold during this initial phase in which it will essentially be a primary gold mine. This will increase PNG's total gold output noticeably, but these high levels of production will not be maintained beyond about 6 yr, which is the estimated life of the gold cap. Beginning probably in 1989–90, Ok Tedi will process copper ore only with a small amount of byproduct gold production.

Two of PNG's prospective gold producers are the Porgera and Misima Island primary gold prospects. The Porgera gold prospect is reported to contain 6.7 million tr oz gold (*67*, p. 144) and Misima Island 1.3 million tr oz (*68*, p. 23). Currently, neither prospect is under development, but exploration is ongoing. Thus, the near-term expectation is that PNG's total gold output will rise sharply due to Ok Tedi's initial production and then decline after the initial phase of primary gold mining at Ok Tedi is completed. Thereafter, it is expected that PNG production will remain at 500,000 to 700,000 tr oz/yr and be almost completely

Table 71.—Annual gold production in 10 important gold producing countries, 1975–83, thousand troy ounces[1]

	China	Philippines	Papua New Guinea	Chile	Zimbabwe	Colombia	Dominican Republic	Ghana	Peru	Mexico	Total
1975	50	502	611	129	500	308	195	524	101	145	3,065
1976	80	501	668	129	387	300	413	532	121	163	3,294
1977	100	559	740	116	402	263	343	481	104	213	3,321
1978	150	587	751	102	399	257	343	402	113	202	3,306
1979	200	535	630	111	388	269	353	357	124	190	3,207
1980	225	644	452	220	368	510	370	353	142	196	3,480
1981	1,700	758	540	400	371	535	408	341	162	203	5,418
1982	1,800	835	564	543	426	481	380	331	158	196	5,714
1983	1,900	817	582	571	430	429	348	303	166	223	5,754
1984 (estimated)	[2]1,900	[2]780	[2]577	[2]553	[2]430	[2]439	[2]339	[2]320	170	[2]216	5,724

[1]Sources: Bureau of Mines (*1*, *20*), except where noted.
[2]Source: Gold Institute (*2*).

dominated by byproduct output from Bougainville and Ok Tedi in the absence of other primary gold or copper mine developments in the 1990's.

CHILE

Chile has shown a large increase in annual gold production, from 129,000 tr oz in 1975 to 571,000 tr oz in 1983. A recent article by Crozier (*69*) contains a detailed breakdown of gold production for the years 1976 and 1982, which has been summarized in table 72. As shown in the table, gold output increased fourfold from 1976 through 1982. Of this overall increase in annual gold output of approximately 410,000 tr oz, 89 pct came from primary gold mines, 10 pct came from increased byproduct production from copper mines, and only 1 pct came from primary silver mines.

Table 72.—Breakdown of 1976 and 1982 gold production in Chile, by category of mining operation, troy ounces

Type of operation	1976	1982
Primary gold mines:		
Medium size	32,119	404,032
Small size	26,653	17,821
Subtotal	58,772	421,853
Copper mines:		
Codelco	34,781	38,716
Medium size	16,200	49,358
Small size	17,812	23,139
Subtotal	68,793	111,213
Silver mines:		
Medium size	1,607	4,931
Small size	0	778
Subtotal	1,607	5,709
Lead and zinc mines	0	4,794
Total	129,172	543,569

Source: Reference 69.

It is important to note that almost 100 pct of the increase in primary gold production came from the "medium sized" category and that about 350,000 tr oz (94 pct) of this total increase came from the El Indio primary gold mine. El Indio began producing in 1980 and for the first few years was producing from very high grade ore. Beginning in 1985, the El Indio Mine is expected to produce at an average annual rate of around 140,000 tr oz, mining ore of much lower grade than in the first few years of production. Current demonstrated resources are sufficient for production to continue at El Indio until the mid-to-late 1990's. Long-term total production costs are estimated to be under $300/tr oz.

Over the last 3 to 4 yr, there has been much exploration for primary gold deposits along the coastal mountain range north and south of La Serena, at the Sancarron Prospect in the vicinity of the El Indio Mine, north of the El Indio Mine (the El Nevada Prospect), and in the Guanaco district in the State of Antofagasta. Based on the trend shown in table 72, it is expected that any major increase in Chilean gold production above the levels of 1983–84 will have to come from the development of additional primary gold deposits rather than from copper deposits, unless copper production from the medium-sized mines is increased dramatically. For example, CODELCO's annual byproduct gold production from its large copper operations increased by only 3,935 tr oz during 1976–82, which meant that fully 78 pct of Chile's increased byproduct gold production from copper mining during this period came from the medium-sized mines rather than CODELCO's larger operations.

ZIMBABWE

It has been estimated that total historical gold production in Zimbabwe as of 1975 ranged from 65 to 70 million tr oz, which includes 20 to 25 million tr oz of ancient production (*70*, p. 47). During this period of ancient production, Zimbabwe "may have been the greatest gold field of the ancient world" (*4*, p. 137).

Peak gold production in Zimbabwe since records have been kept occurred in 1945–64. During this period, Zimbabwe's reported gold production was fairly consistent at about 525,000 to 575,000 tr oz/yr, reaching the highest level during 1964 (*20*). Since that peak, gold production in Zimbabwe has shown a gradual but steady decline to a low of 368,000 tr oz for 1980 (*3*). Since 1980, the decline has been reversed somewhat, with output rising to 430,000 tr oz for 1983 (*2*), yet this is still below the 500,000- to 550,000-tr-oz/yr level of the late 1960's and early 1970's (*20*).

For this study, 12 primary lode gold operations in Zimbabwe were evaluated. These 12 operations were all producing in the 1981–82 period and should have accounted for a total of around 270,000 tr oz, or 63 pct, of gold production in 1982. The following points can be made about these 12 operations, which reflect the gold mining industry in Zimbabwe as it is presently comprised:

1. All of the lode gold producers studied are small, underground mines. The 12 operations had ore milling capacities, circa 1982, of 60,000 to 265,000 mt/yr and produced 9,000 to 58,000 tr oz/yr gold. Respective averages were about 130,000 mt/yr ore milled to produce 22,000 tr oz/yr gold.

2. The past production histories of many of these 12 operations reflect sporadic periods of production, shutdown, and reopening. The longest period of continuous production observed at any of the 12 operations was 40 to 50 yr.

3. As in Canada, the lode gold deposits usually contain a fair amount of free gold and are associated with sulfide minerals (usually pyrite and arsenopyrite). Thus, 8 of the 12 milling operations contained gravity circuits, 6 of the mills had at least 1 flotation stage, and 2 of the mills required roasting of concentrates.

4. Mill recoveries are fairly low with a weighted-average gold recovery for the 12 operations of only 84 pct. Again, this reflects the fairly complex nature of the minerology of typical lode ores in Zimbabwe.

5. The grades of typical ores as of 1982–83 are relatively high, ranging from 3.3 to 12.8 g/mt. The weighted-average feed grade for all 12 operations was approximately 6.2 g/mt.

6. At 10 of the 12 operations studied, the ore mineralization occurs as either pods, veins, bands, reefs, or lodes, which means that at least one dimension is small and mineralization can be erratic. Only 2 of the 12 operations had ore body dimensions that would allow large-scale, high-volume methods of mining to be practiced. For all 12 of the mining operations, the mining widths ranged from 1 to 7 m with an average of 3.4 m.

7. Labor is the most important component of mining cost and is estimated to range from 44 to 68 pct of the total with an average of 57 pct. This percentage could increase since Zimbabwe has been experiencing a rapid increase in mining labor wage rates since independence in 1980.

8. Milling costs are relatively high at $9/mt to $20/mt, with labor accounting for only 30 pct of the total milling cost, on average.

9. Total recoverable gold at these 12 evaluated operations is estimated at 3 million tr oz, with 37 pct of this total represented by the Renco Mine.

10. Long-term total production costs range from $250/tr oz to $600/tr oz, although 70 pct of total recoverable gold is available below a break-even cost level of $400/tr oz.

Since major lode gold operations in Zimbabwe average approximately 22,000 tr oz/yr production, about 20 new mining operations of comparable size would have to be developed to double 1984's estimated annual production capacity. Although much of Zimbabwe has a geologic environment that is conducive to the occurrence of lode gold deposits, the sporadic nature of the mineralization, the complex mineralogy of the ores, and present economic conditions all argue against a fast and large increase in annual gold production.

COLOMBIA

Total gold production in Columbia from 1570 through the early 1980's is conservatively estimated at 60 to 80 million tr oz. This amount of total production means that Colombia is probably the sixth or seventh largest gold producing country throughout history. It should be noted that the estimate does not include production for most of the 16th century or production prior to the coming of the Spaniards in the early 16th century.

During the 20th century, the peak year for annual production of gold in Columbia occurred in 1981 when 535,000 tr oz was produced. However, in terms of a sustained high level of annual production, 1944–63 appears to have been the peak period. During these 20 yr, annual production in Colombia ranged from 325,000 to about 460,000 tr oz, with an average annual output of 406,000 tr oz. The ensuing years of 1964 through 1972 saw a steady decline in annual gold production from 365,000 tr oz for 1964 to only around 175,000 tr oz for both 1971 and 1972, a decline of over 50 pct. With the freeing of the price of gold in 1971–72, a rebound in Colombian gold production occurred, from 175,000 tr oz in 1972 to 308,000 tr oz in 1975 (*20*). Since that time, Colombia's gold production has fluctuated from a low of 257,000 tr oz in 1978 to a high of 535,000 tr oz in 1981 (table 73).

Colombia's annual production (like Brazil's) more rapidly reflects the effects of the varying price of gold. For example, the average price of gold fell 30 pct in 1981–83, and Colombia's gold production dropped 24 pct. The reason for this heightened sensitivity of production to the price of gold lies in the makeup of the gold operations. A majority of total gold production comes from small, alluvial gravity operations with little equipment; these operations are usually family-run, and can be brought into production quickly or shut down immediately as the price of gold varies.

Table 73 places the distribution of gold production in Colombia, as of 1981–82, into perspective. As shown, Antioquia Province accounted for 70 pct and Choco Province accounted for 20 pct of total gold production during this period. These two provinces have historically accounted for the vast majority of Columbian gold production. In 1981, only three operations (two dredging and one lode mining) were producing more than 20,000 tr oz/yr. These three operations were estimated to account for 115,000 tr oz (21.5 pct) of the total 535,000 tr oz that was produced in 1981. The small operations mentioned in table 73 are really very small. The average size small producer in Antioquia Province in 1981 was only producing an estimated 1,675 tr oz/yr gold, while those in Choco Province were estimated to be producing only about 570 tr oz/yr gold. Yet, combined, these small operations represented 78.5 pct of 1981 production.

Table 73.—Estimated distribution of 1981 Colombian gold production, by province and size of operations

Province and size of category	1981 production, 10^3 tr oz	Description of operations
Antioquia Province:		
Major producers	65	1 dredging operation, 1 lode mining operation.
Minor producers	310	185 small producers, average size = 1,675 tr oz/yr.
Total (70 pct).....	375	NAp.
Choco Province:		
Major producers....	50	1 dredging operation.
Minor producers....	57	100 small producers, average size = 570 tr oz/yr.
Total (20 pct).....	107	
Other Provinces (10 pct)	53	NAp.
Total............	535	NAp.

NAp Not applicable.

In 1982, one of the major dredging operations shown in table 73 was shut down; however, a new dredging operation in Antioquia Province was supposed to begin production in late 1982 at slightly more than 30,000 tr oz/yr. The major lode gold mining operation appeared as of 1981 to be in decline, in terms of both production and reserves, with indications that it would be hard-pressed to remain in production past 1985. It has been reported that an old lode mine (the Marmato Mine) may be reopened by 1986 (*71*, p. 433); however, the reported production capacity would only be 20,000 to 25,000 tr oz/yr gold. No other major developments have been announced in the last few years; thus, it is felt that the immediate future of gold production in Colombia still lies with the small operations. If this is the case, then it may take another major increase in the gold price before there are significant increases in annual gold production.

DOMINICAN REPUBLIC

Annual gold production (table 71) in the Dominican Republic increased from 195,000 tr oz in 1975 to 413,000 tr oz in 1976 and has remained in a range of 343,000 to 408,000 tr oz/yr since 1976. The Dominican Republic's gold production represents output from only one mining operation, the Pueblo Viejo Mine of Rosario Dominicana, S.A., which started production during 1975 and did not reach full capacity until 1976. This operation is estimated to have total production costs over its remaining life of well below $200/tr oz, which places it among the 10 lowest cost producers that were evaluated in this world study.

Since the start of production, the Pueblo Viejo operation has been processing oxide ore only, and the cost estimates derived for this study reflect only the processing of oxide ore. Present oxide reserves should last until 1991 at current production; however, sometime in 1985 or 1986 a decision will have to be made as to whether to attempt processing the underlying sulfide ores, which could add 30 to 36 yr of additional life to the operation. The sulfide ore is lower grade than the oxide ore and will require a revised mill with higher processing costs and/or lower recoveries. Thus, gold production in the Dominican Republic will probably remain in the range of 300,000 to 415,000 tr oz through the year 1990, with any projection beyond that date dependent upon the decision reached regarding treatment of the sulfide resources and the results of ongoing exploration for additional oxide ore zones.

GHANA

Ghana, the former Gold Coast colony of Britain, probably contributed a significant portion of the gold output from the African continent prior to 1492, with the vast majority of this production coming from small alluvial operations. The first major mining of gold by European interests began in 1878–82 with development of the banket (bedded) gold deposits at Tarkwa. Production from the lens gold deposits of Prestea first began in 1890, and production from the lens deposits at Ashanti began in 1897. These three primary gold deposits have formed the core of Ghana's production since 1900 and have produced continuously except during 1939–45. A fourth major primary gold producing operation in Ghana is the dredging operation in the Dunkwa alluvial goldfield.

No major primary gold producing operations have been developed in Ghana since 1938 (*4*, p. 140). Gold production in Ghana reached its highest level in 1963 with production of 921,555 tr oz (*20*) at an indicated recoverable grade of 33 g/mt. Since 1963, a steady decline in gold production has occurred, to 614,000 tr oz for 1974 and to 303,000 tr oz for 1983, a drop of over 66 pct since the peak production year of 1963. Ghanian officials were estimating in 1979–80 that as much as $36 million worth of gold was being smuggled out of the country each year (*4*, p. 140), this represents at least 100,000 tr oz/yr additional gold production, which probably does not show up in reported production amounts.

Table 74.—Gold production in Ghana, 1964, 1980-81, and 1983, by major producing entities,[1] thousand troy ounces

	1964	1980–81	1983
Ashanti	471	312	229
5 state-owned operations	374	98	50
Subtotal	845	410	279
Difference from reported total production	+20	+15	+24
Total reported production	865	425	303

[1]Compiled from various issues of the Bureau of Mines Minerals Yearbook and other sources.

With the achievement of independence in 1960, the Ghanian Government established a state-owned corporation, the Ghana State Mining Corporation, as a holding company for the five gold mines operating in the early 1960's: Amalgamated Banket Areas, Arista, Ghana Main Reef, Bibiani, and Bremary Gold Dredging. By 1964, there were only two privately owned gold mining operations in Ghana, the Ashanti operation and the small Konongo Mine. As of 1979–80, there was only one gold mining operation with partial (45 pct) private ownership, the remainder being controlled by the State Gold Mining Corporation.

For the year ending June 1981, production at Ashanti was about 290,000 tr oz, while total production at Tarkwa and Prestea was about 86,000 tr oz for combined output from all three operations of 376,000 tr oz. Production from the other two state-owned gold operations (the underground Konongo Mine and the Dunkwa dredging operations) was probably similar to 1976 production with output of 3,200 and 9,600 tr oz, respectively, bringing total output for the period to 388,000 tr oz/yr.

Table 74 compares estimates of production from Ashanti and from the five major operations of the State Gold Mining Corporation with total country production for 1964, 1980–81, and 1983. Actual comparison of production values is difficult because of differing financial years, resulting in the entry entitled "difference from reported total production" on the table and the apparent discrepancy in yearly production figures cited in the text. As shown, even though Ashanti's production had fallen by 242,000 tr oz (51 pct), from 1964 through 1983, its percentage of total gold production in Ghana has actually increased from 54.5 pct in 1964 to an indicated 75 pct in 1983.

The 1983 gold production figures show an industry in disarray. Production at the state-owned operations has fallen nearly 50 pct in just 3 yr, while production at Ashanti has fallen by 27 pct. This decline has alarmed the Government sufficiently so that in late 1983 and early 1984 it took several steps in an attempt to return production to levels comparable to those of the early 1960's (900,000 tr oz/yr). The changes instituted so far are a 90-pct devaluation of the Ghanian currency (the cedi) in October 1983, the granting of the right for a corporation to retain 20 pct of its export earnings, and allocation of the bulk of a recent IMF funding program to attract foreign investment. Goals of the program are to double production at Ashanti to about 450,000 to 460,000 tr oz/yr by 1989 and to triple output at the state-owned mines to 150,000 tr oz/yr by mid-1987. A new shaft will be sunk at Ashanti and $25 million of new equipment will be purchased as part of its program, while operations at Tarkwa, Prestea, and Dunkwa will be rehabilitated beginning with an International Development Agency loan of $23.7 million (*72*, p. 212).

Whether these plans can be achieved or not remains to be seen. There are many negative factors affecting the Ghanian gold industry, among them the shortage of qualified personnel and the lack of financial capital. There is a great need for new investments at these very old mines that have been in operation anywhere from 91 to 106 yr and have expanded laterally to such an extent that new shafts and new, modern equipment are major priorities. The grades of the three major lode mines in Ghana are excellent, ranging from 5.8 to 12.5 g/mt, and there is good potential for additional resources. Thus, there should be no reason, given an environment conducive to efficient operation, that these mines could not attain the goals set out above.

This study attempted to determine current demonstrated gold resources and long-term total production costs at the Ashanti, Tarkwa, and Prestea gold mining operations. The results are an estimated 6 million tr oz of recoverable gold available from all three operations, with roughly two-thirds of this total recoverable gold represented by the Ashanti Mine. Extraction of this gold, as estimated in this study, is indicated to be very expensive at over $700/tr oz. However, this estimate is based upon negative technologic and economic factors as of 1981–82 which could possibly be overcome by radical change.

PERU

Annual production of gold in Peru increased 64 pct between 1975 and 1983, with virtually 100 pct of the increase coming from many small, primary gold producing operations mining alluvial or lode deposits in the eastern half of the country. One source states that 10 pct of total 1981 gold production in Peru came from three companies producing from primary gold ores (*73*, p. 360). This would indicate average production at these three companies of about 5,230 tr oz/yr, very small by world standards. There has been no information in the mining press about any large-scale primary gold operations being developed between 1975 and 1981 in Peru. The largest planned primary gold mining operation appears to be a dredging operation, which would produce 16,000 tr oz/yr when brought into production (*73*, p. 360). Basically, at 170,000 tr oz/yr gold production and with a ranking as the 15th largest gold producer, Peru is not a significant factor in the world's gold industry.

MEXICO

Mexican gold production showed a moderate (78,000-tr-oz) increase from 145,000 tr oz in 1975 to 223,000 tr oz in 1983. In fact, the production values in table 71 show that the increase actually occurred between 1975 and 1977, with annual gold production in Mexico for 1982 and 1983 virtually identical to that in 1977. During this period, the majority of Mexican production has come from two smelting-refining complexes: the Torreon lead-zinc complex, which handles ores and concentrates from the major lead and silver mines, and the Cananea copper complex, which handles concentrates from the Cananea copper mine. It is estimated that in 1982 about 85 pct of total Mexican gold production came from these two smelting-refining complexes; the Torreon smelting-refining complex produced about 155,000 tr oz, and the Cananea complex produced about 12,000 tr oz.

As of 1982, there was only one deposit in Mexico that could be classified as a primary gold deposit, and there were no primary gold producers. For example, of the 16 Mexican gold-silver properties initially investigated for this study, only 3 had gold grades high enough to be considered as primary gold mines, and the 2 producing operations in this group were actually primary silver mines. Thus, only 1 of the 16 properties (Pinzan Morado) is classified as a primary gold deposit, and it is still not in production as of 1984.

Recent publications mention that trial production was begun in February and March 1984 at a new primary gold mine (El Barqueno) which was not evaluated for this study. One source (*75*, p. 25) mentions that this deposit plus another nearby deposit (Los Murillo) could increase Mexico's gold production by 24,000 to 48,000 tr oz for 1984 and could add 177,000 tr oz of additional production by 1987 or 1988. To achieve this output from these two deposits would probably require an ore capacity of about 1 million mt/yr, which in turn indicates that reserves of 8 to 10 million mt would be required. Current reserve estimates are below 8 million mt. It is fairly certain, though, that any major increase in Mexican gold production over the near term will have to come from deposits such as these two.

POSSIBLE GOLD PROJECTS IN COUNTRIES NOT EVALUATED

A review of the 1979–84 mining literature attempted to determine which of the many possible new gold mines that have been announced during this period would be of sufficient potential to have some effect on world mine production of gold. The list, presented in table 75, represents only those gold deposits that (1) were not in production as of 1982, (2) are not in any of the countries discussed in-

Table 75.—Possible new gold mining developments of significance in countries not covered in the report

Country and deposit name	Estimated possible annual production, 10^3 tr oz
Algeria: Tiririne	30
Czechoslovakia: Sedicany	175
Fiji: Vatukoula JV (Emperor)	40
Greece: Neo Khorion	60
India: Chigarikunta	20
Chittor District	20
Indonesia: Lebong Tandai Arca	30
Ivory Coast: Ity	40
Japan: Hishikari	115
New Zealand: Martha's Hill	85
Saudi Arabia: Mahd Adh Dhahab	75
Suriname: East Suriname Project	20
Upper Volta: Poura	75
Total	78

dividually in this report, (3) appear to have sufficient reserves to allow production of at least 20,000 tr oz/yr gold, and (4) have resource values that appear to be reasonably well documented. As shown, only 13 deposits met the criteria above, although this undoubtedly is not an all-inclusive list.

Four of these 13 possible operations are past producers that have been reevaluated in light of increased gold prices, and 1 is a deposit first reported on as early as 1971. Only 8 of the 13 represent, as far as is known, totally new discoveries during the late 1970's and early 1980's.

If all 13 were brought on-line, they would represent close to 800,000 tr oz of additional annual gold production with an average output of 60,000 tr oz/yr. However, 3 of the 13 are low grade (less than 3.0 g/mt), raising questions about whether the price of gold as of 1984 is sufficient to allow development to proceed. Even if all 13 operations were developed, their output would only represent an increase of around 2 pct in annual world production. Thus, those countries that are currently insignificant contributors to world gold output are likely to remain insignificant, given what is being reported about their potential for expansion.

REFERENCES

1. Lucas, J.M. Gold. BuMines Mineral Commodity Profile, 1985, 16 pp.
2. Gold Institute (Washington, DC). World Mine Production of Gold, 1982-1986, Jan. 1984, 9 pp.
3. Consolidated Gold Fields PCL (London). Gold 1982. May 1982, table 1.
4. Mohide, T.P., K.R. Glasspool, S.A. Hiemstra, D.A. Pretorius, and E.S.A. Antrobus. Gold. Can. Minist. Nat. Resour., Toronto, Ontario, Miner. Policy Background Paper 12, 1981, 275 pp.
5. Whiteside, H.C.M. Gold in the Witwatersrand Triad. Ch. in Mineral Resources of the Republic of South Africa. S. Afr. Dep. Mines, Geol. Surv., Pretoria, 5th ed., 1976, pp. 39-73.
6. Chamber of Mines of South Africa (Johannesburg). Annual Report. 1979 and 1983.
7. Storrar, C.D. (ed). South African Mine Valuation. Chamber of Mines of South Africa, Johannesburg, 1981, pp. 172-173.
8. Mining Journal (London). Beisa: Another Casualty of the Uranium Market. V. 302, No. 7759, May 4, 1984, pp. 296-297.
9. Phoenix Associates, Inc. Development of Foreign Economic Indices, Phase II Update for South Africa (contract J0225001) BuMines OFR 74-85 1984, pp. F1-F2; NTIS PB 85-215671/AS.
10. Engineering and Mining Journal. Proposed Poplar Mine Would Be Tied to Another Evander Mine. V. 184, No. 10, Oct. 1983, p. 10.
11. World Mining. Rich South African Mines To Merge and Expand. V. 34, No. 6, June 1981, p. 135.
12. Mining Magazine. Ranfontein's Cooke Section—A New Gold Mine for a Famous Old Producer. V. 134, No. 4, Apr. 1976, pp. 261-267.
13. Mining Journal (London). South African Output To Remain High. V. 302, No. 7761, May 18, 1984, p. 333.
14. Pretorious, D.A. Gold, Geld, Gilt: Future Supply and Demand. Econ. Geol., v. 76, 1981, pp. 2032-2046.
15. Engineering and Mining Journal. V. 183, No. 11, Nov. 1982, 202 pp.
16. Adamson, R. J. Gold Metallurgy in South Africa. Chamber of Mines of South Africa, Pretoria, 1973, pp. 203-255.
17. Simons, F.S., and W.C. Prinz. Gold. Ch. in United States Mineral Resources. U.S. Geol. Surv., Prof. Paper 820, 1974, pp. 263-275.
18. Merrill, C.W., and H.M. Meyer. Gold and Silver. Ch. in BuMines Minerals Yearbook 1949, pp. 553-587.
19. Budtzen, T.K., G.R. Eakins, and C.N. Conwell. Review of Alaska's Mineral Resources. AK Dep. Nat. Resour., Office Miner. Dev., 1982, 51 pp.
20. U.S. Bureau of Mines. Minerals Yearbooks (various dates).
21. Rosenkranz, R.D., R.L. Davidoff, and J.F. Lemons, Jr. Copper Availability—Domestic. A Minerals Availability System Appraisal. BuMines IC 8809, 1979, 31 pp.
22. Kilgore, C.C., S.J. Arbelbide, and A.A. Soja. Lead and Zinc Availability—Domestic. A Minerals Availability Program Appraisal. BuMines IC 8962, 1983, 30 pp.
23. Canfield, K.S. North American Gold Outlook. American Mining Congress Convention, Sept. 1984, p. 43, available upon request from P.R. Thomas, BuMines, Denver, CO.
24. Chamberlain, P.G., and M.G. Pojar. Gold and Silver Leaching Practices in the United States. BuMines IC 8969, 1984, 47 pp.
25. McQuiston, F.W., Jr., and R.S. Shoemaker. Gold and Silver Cyanidation Plant Practice. AIME, v. 2, 1981, 263 pp.
26. Guay, W.J., and D.G. Peterson. Recovery of Gold From Carbonaceous Ores at Carlin, Nevada. Trans. Soc. Min. Eng., AIME, v. 254, Mar. 1973, pp. 102-104.
27. Forbes, All Is Not Gold. July 30, 1984, pp. 39-40.
28. Canada Department of Trade and Commerce (Ottawa, Ontario). Chronological Record of Canadian Mining Events From 1604 to 1943 and Historical Tables of the Mineral Production of Canada. 1945, 74 pp.
29. Morrell, L.G. The Mineral Industry of Canada. Ch. in BuMines Minerals Yearbook 1965, v. 4, pp. 47-67.
30. Mining Journal (London). Substantial Increase in Canadian Gold Output. V. 302, No. 7745, Jan. 27, 1984, p. 62.
31. Hogan, J.J. Gold. Ch. in Canadian Minerals Yearbook 1974. Dep. Energy, Mines and Resour. Ottawa, Ontario, 1977, pp. 195-211.
32. Hamilton, S.A. Gold. Canadian Minerals Yearbook, 1982. Dep. Energy, Mines and Resour., Ottawa, Ontario, 19 pp.
33. Laughlin, W.H. Canadian Reserves of Seven Metals. Can. Min. J., v. 103, No. 2, Feb. 1982 p. 53; v. 104, No. 2, Feb. 1983, p. 44; v. 105, No. 2, Feb. 1984, p. 28.
34. Wall Street Journal (New York). Pamour Plans To Close Three of Its Gold Mines, Lay-off 480 workers. July 10, 1984, p. 10.
35. Eddington, B. Hemlo Gold Decision Near. Can. Min. J., v. 103, No. 6, June 1982, pp. 47-48.
36. Mining Journal (London). V. 301, No. 7727, Sept. 30, 1983, p. 23.
37. Northern Miner. Teck Keeps Low Profile in Hemlo So Far. V. 69, No. 46, Jan. 19, 1984, p. B38.
38. World Mining. Gold Discovery Draws 70 Companies to Hemlo District. V. 36, No. 5, May 1983, p. 75.
39. Mining Journal (London). Williams Property More Reserves. V. 301, No. 7739, Dec. 16, 1983, p. 442.
40. Scales, M. Dickenson Cashes In on New Mining Strategy. Can. Min. J., v. 104, No. 6, June 1983, pp. 24-34.
41. Ross Lontheran Publications Pty. Ltd. (Western Australia). Register of Australian Mining. 1980, pp. 137-154.
42. Victorian Office of the Commonwealth, Bureau of Census and Statistics. Minerals in Victoria. 1973 (reprint), pp. 1-11; available from Victoria Dep. Mines, Melbourne, Australia.
43. Australian Bureau of Mineral Resources, Geology and Geophysics and Australian Bureau of Statistics. Aust. Miner. Ind., v. 33, No. 4, 1980, p. 171.
44. Mining Journal (London). Harbour Lights Reserves. V. 302, No. 7755, Apr. 6, 1984, p. 230.
45. Mining Magazine. Kidston Gold. V. 150, No. 3, Mar. 1984, p. 199.
46. Engineering and Mining Journal. Olympic Dam Bids for a Place Among the World's Great Mines. V. 184, No. 11, Nov. 1983, p. 62.
47. Latin American Mining Letter, Metals and Minerals Publication (London). May 4, 1984, pp. 2-3.

48. Mining Journal (London). Central Bank Buys More Gold. V. 302, No. 7758, Apr. 27, 1984, p. 281.
49. ———. Gold Brazil's Bright Spot. V. 301, No. 7716, July 8, 1983, pp. 24-25.
50. Wall Street Journal (New York). Brazilian Gold Prospectors Hit Pay Dirt. Oct. 1, 1984, p. 33.
51. Engineering and Mining Journal. Brazil Strives To Harness Serra Pelada Gold Rush. V. 181, No. 10, Oct. 1980, p. 55.
52. Barron's (New York). Brazil Spurs a New Gold Rush To Refill Its Coffers. Mar. 26, 1984, p. 79.
53. U.S. Embassy, Rio de Janeiro, Brazil. State Dep. Airgram A-28 Attachment, Sept. 18, 1980, p. 2.
54. Companhia de Pesquisa de Recursos Minerais (CPRM) Brasilia. Situacao do Ouro do Brazil (The Situation of Gold in Brazil). Serie do Ouro, No. 5, Feb. 1980.
55. DeBatz, R. The Auriferous Deposits of Siberia. Proceedings of Atlantic City Meeting, February 1898, Atlantic City, NJ, pp. 452-467, available from P.R. Thomas, BuMines, Denver, CO.
56. Engineering and Mining Journal. Russian Gold. V. 136, No. 6, June 1935, pp. 273-278.
57. Dowie, D.L., and M. Kaser. A Methodological Study of the Production of Primary Gold by the Soviet Union. Prepared for Consolidated Gold Fields, July 25, 1974, 21 pp.; available upon request from P.R. Thomas, BuMines, Denver, CO.
58. Cieslewicz, W.B. Russian Gold and the Dollar Crises. Mines Mag., V. 63, No. 12, Dec. 1973, pp. 4-9.
59. Mining Journal (London). USSR To Produce More Gold? V. 284, No. 7280, Feb. 28, 1975, p. 158.
60. World Mining. Soviet Byproduct Gold Production. V. 34, No. 6, June 1983, pp. 64-70.
61. Lewis, P. Gold-Mining Boom in Soviet Forecast. New York Times, Apr. 11, 1983.
62. Mining Journal (London). Soviet Union. -Mining Annual Review, 1974. June 1974, pp. 426-448.
63. ———. Soviet Union. -Mining Annual Review, 1977. June 1977, pp. 559-581.
64. Stewart, J.M. Siberia, No Longer A Sleeping Land. Optima, v. 26, No. 2, 1976, pp. 85-104.
65. International Monetary Fund. International Financial Statistics. V. 37, No. 10, Oct. 1984, pp. 44-47.
66. Mining Journal (London). One Year Delay for OK Tedi Copper. V. 302, No. 7761, May 18, 1984, p. 332.
67. ———. Porgera Extension. V. 302, No. 7750, Mar. 2, 1984, p. 144.
68. Placer Development Ltd. (Vancouver, British Columbia). Annual Report, 1982. P. 23.
69. Crozier, R.D. Gold Mining in Chile. Min. mag., V. 150, No. 5, May 1984, pp. 460-461.
70. Anhaeusser, C.R. The Nature and Distribution of Archaean Gold Mineralization in Southern Africa. Miner. Sci. and Eng., v. 8, No. 1, Jan. 1976, p. 47.
71. Mining Magazine. Colombian Gold. V. 150, No. 5, May 1984, p. 433.
72. Mining Journal (London). V. 302, No. 7754, Mar. 30, 1984, p. 212.
73. Empresa Minera Del Centro Del Peru (Lima, Peru). This Is Centromin Peru. 4th ed., Nov. 1977, 23 pp.
74. Mining Journal (London). Mining Annual Review, 1982. June 1982, p. 360.
75. Engineering and Mining Journal. Mexico Moves Quickly To Exploit New Gold Find. V. 185, No. 4, Apr. 1984, p. 25.

APPENDIX.—METHODOLOGY OF ANALYSIS

The analyses performed for the purposes of this study involved geologic, engineering, and economic evaluations.

The geologic aspects particular to each current or proposed gold mining operation included in the study were determined in order to develop estimates of demonstrated recoverable resources and weighted average mill feed grades.[1] Demonstrated resource tonnages are reported in metric tons and mill feed grades in grams per metric ton.

An aggregate summarization of demonstrated resource tonnages, mill feed grades, and contained and recoverable gold in troy ounces is reported for each country. These estimates were developed on a property-by-property basis but are aggregated in order to preserve the confidentiality of some of the data. All resource estimates are as of January 1984.

The demonstrated resource level was employed for costing purposes in order to determine the relative economic position of each operation and each country evaluated. For the base case cost analyses, all cost and resource estimates were updated to January 1984. Mining and beneficiation methods and costs were developed according to actual or proposed development plans and associated production capacities, including all announced capacity expansions as of 1981–82. The estimates of mining and beneficiation operating costs are on a per ton of ore feed basis and are composed of three components: direct and indirect labor costs, equipment operation costs, and material and supplies cost. The operating cost estimates do not include allowances for capital recovery (depreciation), taxes, royalties, or reinvestments in plant and equipment. These costs are calculated and entered into the analyses separately.

The engineering evaluation outlines the major mining and beneficiation methods, costs, and operating parameters. The countries are then ranked by resource level and degree of economic competitiveness, as measured by the estimates of mining and milling operating cost. Operating costs are estimated to reflect the cost of mining an entire demonstrated resource and include such factors as increasing underground haulage distance, mining depth, capacity expansions at the mine and milling facilities, declining ore grade, etc. The cost estimates are long-run in nature and are generally higher than current operating costs. In addition, mine, mill, and infrastructural capital costs and development expenses are determined, and any exploitation or development problems that are significant in affecting gold availability are also addressed. Mine and mill plant and equipment reinvestments required over the mine life are also included in order to determine total capital costs.

To determine the cost and quantity of refined gold of at least 99.6-pct purity that is potentially available from each property's demonstrated resources, the analyses were expanded to include, where applicable, gold dore refining and concentrate smelting and refining costs and gold dore and concentrate transportation, handling, and insurance costs.

Lastly, all existing foreign country tax structures that relate to capital recovery and taxation of income were incorporated into the analyses in order to perform a complete economic evaluation.

The economic evaluation of each operation was performed using discounted cash flow rate of return (DCFROR) techniques. The base case analyses consisted of two parts. In the first part, the long-run total cost of producing refined gold from each operation over its producing life was determined. This cost is defined mathematically as a discounted cash flow unit (per ounce) cost and is herein referred to as the long-run total production cost or total cost. The long-run total cost equals the long-run U.S. dollar-denominated price per ounce at which gold must be sold, so that the present value of all revenues equals the present value of all costs, including a prespecified rate of return.

For this study, rates of return of zero and 10 pct were specified when determining the long-run total cost of production over the life[2] of an operation. The first rate (zero percent) is used to determine the break-even point, where revenues are sufficient to cover total investment and production costs over the operation's life but provide no positive rate of return. This is the undiscounted cost determination. This rate would reflect the investment parameters of a project given only market share or developmental concerns, where potential multiplier effects (i.e., social benefits) would offset company-operation-specific profitability. For privately owned enterprises or those not strictly developmental in nature nor Government owned, a more reasonable long-term economic decision-making parameter is that represented by the 10-pct DCFROR. This rate was considered the minimum sufficient to maintain adequate long-term profitability and attract new capital to the industry. Within these two economic horizons lies the cost structure of the operations and countries in question. The second part of the economic evaluation determined long-run rates of return, given assumed constant 1984 gold prices (usually $400 and $500) and a discount factor of 10 pct.

The availability of gold from an operation is presented in this study in two ways. First, gold availability is presented as a function of the long-run total production costs associated with it. Total availability curves are constructed as aggregations of all evaluated operations, ordered from those having the lowest total production costs to those having the highest. The potential total availability of gold can be seen by comparing the expected 1984 U.S. dollar market price to the total cost values shown on the availability curves. Second, annual availability curves for selected time periods are constructed that show the annual availability of gold at different cost-price levels.

[1]Recoverable resource is defined as total mill feed tonnage and contained gold after allowances for mining recovery and dilution.

[2]The project life of each property evaluated was determined by assuming that the property would be operated at 100 pct of design capacity for producing operations, or for nonproducing operations, as determined according to the engineering development plan that was derived. The mine life covers only the demonstrated resource level.

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